The form and structure of the tertiary dyke-swarms af Skye and Ardnamurchan

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THE FORM AND STRUCTURE
OF THE TERTIARY DYKE-SWARMS
OF SKYE AND ARDNAMURCHAN

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"And only the smell of the sea, with a few bristly bushes of gorse and coarse tufts of heather, among the grey, pellucid rocks, in the grey, more pellucid air. The coldness, the greyness, even the soft, creeping fog of the sea, and the islet of rock humped up in it all, like the last point in space."

D.H. Lawrence,

"The Man Who Loved Islands"

ABSTRACT

A study of the characters of the Tertiary dyke-swarms of Skye, Ardnamurchan and the Small Isles of Inverness-shire is based on observations at over 7500 dyke-outcrops, most of which are located along well-exposed traverses. Because of geological limitations analyses of the properties of the dykes (trend, dip and thickness) can be semi-statistical only.

Each of the dyke-swarms consists of a regional linear component of N.W. to N.N.W. trending dykes, including parallel secondary-swarms in Skye and Ardnamurchan, together with in Skye and Rhum N.E. subswarms of distinctive geographic distribution and comparatively low intensities. The observations taken have facilitated: (a.) the construction of contour-maps depicting symmetrical distributions of multiple-dykes, of the arithmetic-average trends and thicknesses of the dykes, etc., (b.) both an approximate delimitation of regional-swarms and the distinction of these from subsidiary-swarms, in each case on the basis of the intensity-distribution and trend-distribution of the constituent dykes, and (c.) the discovery of a latent plutonic complex near Muck, and a possible "centre" off the north-west coast of Lewis.

The trends, thicknesses, and to some extent the dips of small groups of dykes are intimately related to: (i.) the locations of those dykes with respect to the axes of high-intensity of both crustal-stretch (dilation) and number of dykes per kilometre, (ii.) the positions of the dykes in relation to the site of the roughly contemporaneous Central Intrusive Complexes, and (iii.) the structure of the country-rock in which the dykes were emplaced, especially in the

cases of the Moinian rocks, the Tertiary lavas, and the peripherally folded Mesozoic rocks bordering the Central Complex of Skye.

The form and structure of the dyke-swarms, the distribution of the petrological types of dykes, and the available aeromagnetic, gravity-anomaly, and radiometric-dating evidence, indicate that the emplacement of each dyke-swarm is related to a zone of N.W. transcurrent faulting roughly paralleling the major dilation-axis of the swarm. Such faults were the consequence of differential movement of crustal blocks away from the line of a proposed Tertiary separation (Rockall Trough) of the British mainland and Rockall Plateau. Intracrustal, elongate, ridge-like basaltic magma-reservoirs, whose ultimate source was the upper mantle, are believed to have ascended each of these faults. At the intersections of the N.W. transcurrent faults with pre-existing N.E. faults cylinders of basaltic magma arose to form the Central Intrusive Complexes. Dyke-swarms developed as offshoots of the basaltic ridges and to a small extent from the basaltic cylinders, under the influence of a N.E. to S.W. tension resulting from a relative separation in this same direction of the crustal blocks on both sides of the Rockall Trough rift.

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INTRODUCTION

1:I. Opening Statement.

In his presidential address, Evans (1925,p.lxxx) stated that "comparatively little attention has been given to the occurrence of tension in areas where it has left evidence of its existence in the form of joints, normal or slip-faults (occasionally replaced by monoclinal folds), or of dykes and other characteristic igneous phenomena". Later in the same discourse Evans (1925,p.lxxxviii) made the added comment that, "Evidence of regional tension in an area characterized by igneous activity will frequently be afforded by numerous parallel dykes (mostly basic in composition) which follow the direction of the jointing at right angles to the main direction of tension, and in some cases a smaller number of conjugate dykes at approximately right angles to the former. The total thickness will furnish a measure of the extension at right angles to them, except so far as any of them are formed by replacement of the country-rock".

By no means was Evans the originator of these ideas. Many previous decades of research and thought by others had led him to formulate his words with such acumen. It is the design of this thesis to fulfil the challenge which is implied in those words, and to this end as much data, as time has permitted, on the Tertiary dyke-swarms of Skye and Ardnamurchan, has been accumulated.

A study of the available documented previous work, on the general topics of dykes and dyke-swarms, reveals only too clearly the high degree of probability that the forms of some types of, if not all, dyke-swarms obey certain laws. The purpose of the work on the Tertiary dyke-swarms of Skye and Ardnamurchan is to reveal such laws or rules, and to attempt to verify or annul certain hypotheses of earlier workers on these and other swarms throughout the world.

A favourable opportunity arises in these opening paragraphs to express the author's indebtedness to a certain eminent geologist for the guidance which his work has provided. Above all else, it is perhaps the conclusions presented by Richey (1939), on the form, structure and origin of dyke-swarms, which have served as the major incentives to the pursuance of this research. Fig.1 is reproduced from maps which Richey (1939,1961) presented. This sketch of the trends and approximate distributions of the Tertiary dykes, in particular, has been of paramount aid in pre-arranging the conduct of operations in the field.

1:II. Geographical Scope.

The study of the Tertiary dyke-swarms of the Hebrides is somewhat limited by the available exposure. The Area of Study is indicated in fig.2. Unfortunately, much of this area is occupied by sea. The delimitation to the south-west is coincident with the north-eastern limits of the area of study of Sloan (pers. comm.), who has worked on the Tertiary Dyke-

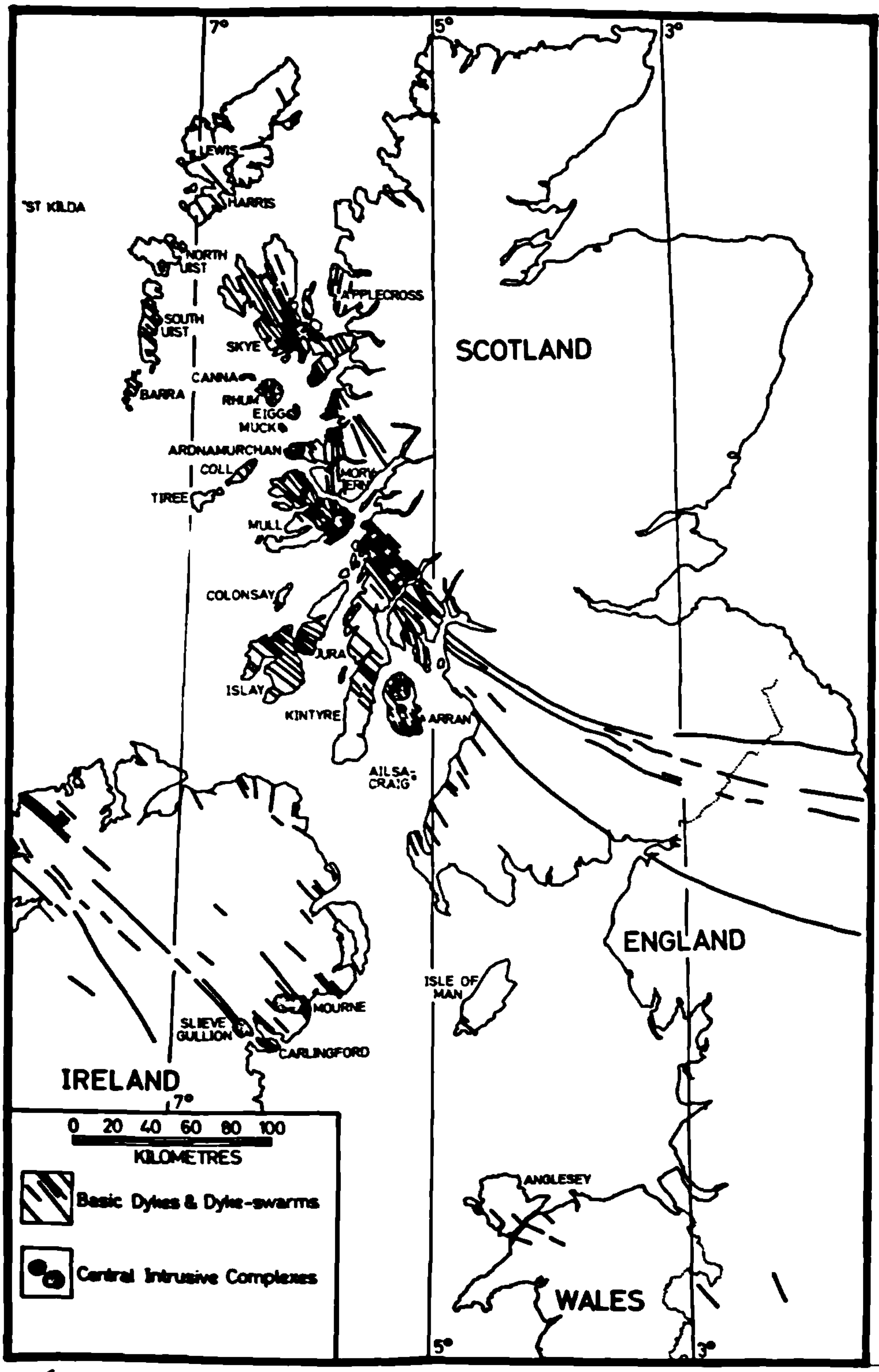


Fig. 1. Trends of the Tertiary dykes of Britain and Ireland. (Derived from The Geology of Ardnamurchan, North-West Mull and Coll, Mem. Geol. Surv., 1930 (J.E. Richey et al.), fig. 4, and from J.E. Richey, The Dykes of Scotland, Trans. Edin Geol. Soc., vol xiii, part iv, fig. 6), 1939

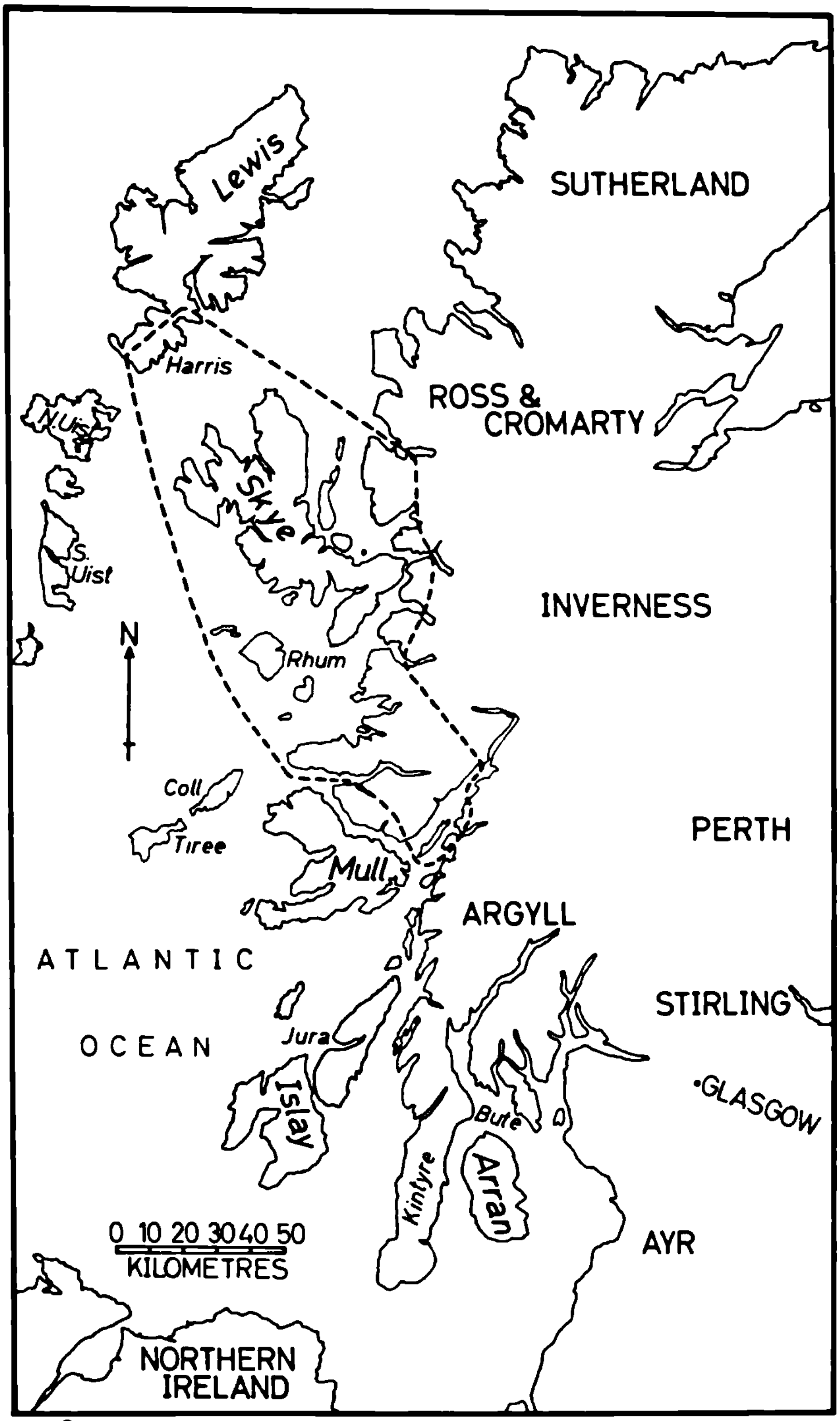


FIG 2. NORTH-WESTERN SCOTLAND. AREA OF STUDY.

Swarm of Mull. Elsewhere the bounds of the Area of Study mark rapid decreases in the intensity of the dykes. Exclusion of Lewis and North Uist from the Area of Study is on the grounds that the intensities of the dykes are extremely low in these islands, and that the dykes of North Uist, and more especially of Lewis, may belong to a different system, i.e. to a different swarm (Ch.7:VII;Ch.13:V).

It is conceivable that in this and later chapters the reader may require assistance with geographical locations: fig.3 is offered as a preliminary aid for this purpose. Should this prove to be inadequate, then fig.47 (in pocket) is furnished with the names of other localities.

Within the Area of Study are the Small Isles of Inverness-shire, viz. Rhum, Eigg, Muck, and Canna. The dykes of the Small Isles are regarded to be of fundamental significance in respect of the questions of both the separation or connexion of contemporaneous swarms and the origin of the Tertiary Hebridean Swarms as a whole. The history of research, the data on the dykes, the conclusions on the form and structure of the Small Isles Swarms, and the geology of these islands are restricted to Chapter 11 et seq. — almost it would seem as an afterthought: in the same vein, indeed, as the work on these islands was undertaken.

1:III. Geological Scope and Aims.

The prime concern is the study of the so-called "Skye

Fig 3. Map of part of Inner Hebrides, largely covering area of study. Locations of some islands, lochs, parishes, villages, headlands, and straits, to which references are made in the text

Dyke-Swarm". (A comprehensive list of definitions of terms relating to dykes and dyke-swarms is given in Chapter 4.) However, it was found that, in order to define the term "Skye Dyke-Swarm" and to complete the study of this swarm, an examination of the behaviour of adjacent Tertiary swarms was necessary. Sloan (pers. comm.) has data on Tertiary dykes in Morvern which form parts of both the Ardnamurchan and Skye Dyke-Swarms. The problem remaining involves the collection and analysis of data on the dykes outcropping on the Ardnamurchan Peninsula, on the Small Isles, on the west-coast mainland of Scotland from Loch Torridon to the southern shores of Loch Linnhe, and on the Isle of Skye, the islands around Skye, and the Island of Harris. As mentioned briefly above, one of the aims is to separate by defining their limits the swarms of Skye, Ardnamurchan, Mull, and the Small Isles, or alternatively to put forth some indication of how they are indivisibly connected. If the latter is the case, i.e. the swarms merge into their adjacent neighbours (Sloan, Speight & Skelhorn, 1969), then some explanation of this phenomenon is required.

Another geological aspect is concerned with the rôle of dykes as fissure-feeders to the lava-flows — in other words, the relation of the basic dykes to the large volumes of plateau-basalt extruded during Tertiary times. The relation of the dykes to the Central Intrusive Complexes is a further avenue of some research.

Lack of exposure, and to a certain degree lack of time has largely limited the collection of data to that on those dykes outcropping within well-exposed sections, although numerous dykes occurring in discontinuously-exposed sections are also recorded. Since, indeed, one of the chief geological aims is to analyse the distribution of the intensity of the dykes, the emphasis where at all possible has been placed on the best-exposed sections. In such sections, for instance, some indication as to the number of dykes per kilometre of section can be accurately ascertained. Obviously, the best sections for acquisition of data on large numbers of dykes are those which are at right-angles to the predominant trend of the dykes. The geography of the area is very favourable in this respect, there being a multitude of well-scoured coastal fringes and a seaboard deeply etched by lochs. The geology is equally kindly disposed to this research, in as much as the Tertiary Hebridean dyke-swarms have suffered little tectonic deformation subsequent to their formation.

Having assembled the data, the aims are to analyse the distribution and/or variation of certain characters:-

(i.) The trend of the dykes.

(ii.) The crustal-extension (or dilation) due to the injection of the dykes. The data collected is that most suitable for the production of a contoured dilation-map, showing the rate of change of crustal-extension.

(iii.) The intensity of the dykes in the form of the function, number of dykes per kilometre.

(iv.) Multiple-dykes.

(v.) The thickness of the dykes.

(vi.) The dip of the dykes.

The results of the above analyses can then be correlated with available geophysical evidence. After this, a comprehensive picture describing the form and structure of the dyke-swarms can be obtained. Subsequently, deductions can be made concerning the origin of these dyke-swarms.

On a broader basis, the results of this work can be used to elucidate the significance of other Hebridean dyke-swarms, and may be extended even further to include interpretations of the forms, structures and origins of swarms throughout the world.

It is regrettable that more of both time and opportunity were not available for a more complete study of certain aspects such as the petrography, the chemistry, and the radiometric-dating of the dykes. Several hundred specimens were collected, and at some future date it is hoped to evaluate the significance of variations in at least the petrology of the dykes.

Chapter Two

REVIEW OF PREVIOUS WORK

2:I. Introduction.

Contributions to the understanding of the form and structure of dyke-swarms, and the mechanisms of origin of these swarms and their constituent dykes, come from two types of source: (i.) the historical record of the work of researchers in the Area of Study, and (ii.) the studies of other dyke-swarms, including not only other swarms of the Thulean Province but also swarms of a variety of ages and structural and petrologic types throughout the world. The significance of the work on dyke-swarms outside the Area of Study is dealt with at appropriate sections in the following chapters, where the relevance (contradictive or affirmative) of the discoveries of other workers to the findings of the present author can be better stressed.

The purpose of this chapter, then, is to detail the major advances in the development of knowledge of the Tertiary Dyke-Swarms of Skye and Ardnamurchan. Certain aspects of this historical review, however, e.g. the ages of the dykes found by comparison with the radiometric-dates of the associated Central Intrusive bodies, and the petrology of the dykes, are dealt with in later chapters (12 & 14).

2:II. The History of Research of the Skye and Ardnamurchan Swarms.

In 1819, MacCulloch noted the abundance of dykes throughout the island of Skye. He remarked particularly on their high density in districts to the south of the Cuillins, where in parts the dykes are equal in aggregate width to the country-rock. Similar high densities were noticed in a belt in Sleat. MacCulloch claimed that two distinct sets of dykes in the regions just to the south and east of the Central Complex of Skye are identifiable. All of the dykes are of late-stage emplacement, according to MacCulloch, since he saw them to traverse rocks of all ages. He was of the opinion that the dykes of Strathaird could have originated from the overlying lavas.

Boué (1820) and von Oeynhausen and von Dechen (1829) did little to add to the already existing knowledge. Zirkel (1870) contributed a petrographic study of the Tertiary igneous rocks. Geikie (1871,pp.283-4) first estimated, on stratigraphic evidence, the age of the Tertiary volcanism as Miocene. However, no considerable additions were made until Judd and Geikie began to argue the source of the Tertiary Hebridean lava-piles.

Judd (1874) postulated that the volcanic-piles issued from five great central volcanoes (Mull, Ardnamurchan, Rhum, Skye, and St. Kilda), the present Central Intrusive Complexes representing the cores of these volcanic cones, each exhibiting a different degree of denudation, Mull the least.

Geikie, conversely, thought that the lava-piles were built up by dyke-feeders. He had already presented evidence that the dykes were contemporaneous with the lavas (Geikie, 1867,p.74), when later he gave the first of a series of papers to the Geological Society of London (Geikie,1871), and papers to other societies (e.g. Geikie,1889), all of which culminated in his classic work, "The Ancient Volcanoes of Great Britain" (Geikie,1897B). In this book he stressed that his belief that the lavas were emitted quietly from fissures was still steadfast. In addition,in 1879, Geikie gave a summary of certain petrographical and physical characteristics of the Tertiary dykes of Britain, and emphasized that there are differences in the intensities of dykes intruded into different country-rocks. Judd, meanwhile, continued to argue in favour of the central volcano (e.g. Judd,1889).

Harker (1904), incorporating many of Clough's observations and embodying the results of earlier work by himself and many others (Geikie,1895,1896,1897A; Clough & Harker, 1899,1904; Harker,1901; Geikie,1898,1899,1900,1901; and Teall,1902), published his findings in a memoir entitled "The Tertiary Igneous Rocks of Skye". Using all the then-available information, Harker described at great length the structural and petrographic features of the rocks of the Central Intrusive Complex, of the lava-pile, and of the dykes and sills. He emphasized the actuality of a general sequence of igneous events from a volcanic, to plutonic, to minor-intrusive phase, and pointed out that the regional dyke-swarm, consisting of a variety of rock types, was intruded spasmodically in sets, certain types being restricted to one period and others being of a recurrent nature. Harker (1904,p.291) commented that the "most striking features of the dykes as a whole are undoubtedly their astonishing number and their general community of direction". He was convinced that the majority of the dykes of Skye dip eastwards, in conformity with a general low-angle tilt (10 to 20 deg.) of the whole region to the west.

Expanding views which he expressed in 1904, Harker (1905,pp.344-5) attempted to relate the Tertiary igneous events in Skye and Rhum, including the emplacement of the regional-swarms of dykes, to contemporaneous, large-scale, "regional" crust-movements of plateau-building type. He also proposed a relationship between the smaller groups of dykes and the intermittent "local" movements of anticlinal type, which often closely followed the lines of pre-Tertiary movements. Harker believed that during the later stages of igneous activity the influence of local crustal strains drew both local and regional dykes into a radiate arrangement about the Central Complexes.

Kynaston and Muff (1908,pp.123-32) observed some narrow dykes of supposed Tertiary age and composed of camptonite, dolerite, variolite, and monchiquite in Lismore and Benderloch, near the southern limit of the Area of Study (figs. 2 & 3).

Clough (in Peach et al.,1910,pp.146-7) remarked on the occurrence of trachyte and trachy-andesite, as well as basalt, dykes in districts south of Loch Alsh, and Peach and Horne (1910) noted the occurrence of Tertiary dykes of N.N.E. trend in the Crowlin Islands.

Richey (Richey & Thomas,1930,pp.343-50) said of the dykes of Ardnamurchan that they are mostly north-westerly, though a few N.E. dykes outcrop at intervals along the entire length of the Peninsula. He also demonstrated that both the acid and the much more abundant basic dykes are of a variety of ages throughout the igneous cycle, although mostly predating the Ardnamurchan ring-dyke complex. Richey noted that multiple-dykes in Ardnamurchan are a rarity.

Richey (1930,p.346) showed that increased intensities of dykes in north-central Mull and south-western Ardnamurchan contrast with lower intensities in north-western Mull, and remarked that the dykes of Ardnamurchan had long been considered to be partly related to the Central Complexes of both Mull and Ardnamurchan. Later Richey (1934,p. 47) reaffirmed this view, saying that the dykes of Kilchoan Bay may belong to the Mull-Swarm.

Davidson (1935) divided the dykes of Raasay, which earlier Lee (1920,p.60)had noted to be the most frequent in Mesozoic country-rocks, into two groups : (i.) a larger group of fine-grained basic types, which have pronounced chilled margins and show little or no baking of the country-rock, and (ii.) a smaller group of coarser types, which have poor chilled margins and show great baking. He suggested that the latter were feeders for the sills and lavas of Raasay, and that the former belong to the Skye regional linear-swarm.

Richey (1939,pp.419-25) gave general indications of the regional variations of the intensities and trends of the Hebridean and Irish Tertiary dykes. He emphasized the connexions of adjacent swarms, and the deviations of the trends of the dykes where such connexions are apparent. Richey (1939,pp.426,431-2) proposed that those Tertiary dykes near the Central Intrusive Complexes may have connected directly to the basic pluton at depth, but that dykes elsewhere must have been fed from an extensive, probably elongate and dome-like, regional magma reservoir. He noted (1939,pp.428-30) that, whereas most of the dyke-swarms of Scotland lie parallel to penecontemporaneous fold-axes, and may have been emplaced during a period of tension which either followed or preceded crustal compression and torsion, the British Tertiary Dyke-Swarms are not related to any such compressive, orogenic movements, excepting N.W. faults and crush-lines.

On the dykes of Ardnamurchan, Richey (1939,p.423) said that their low intensities might be correlated with the narrow and discontinuous border of pre-Tertiary rocks in the Peninsula.

Until 1966, the knowledge was increased but little. Wager and others (1948,p.10) remarked on the variability of composition of the ultrabasic dykes of the Cuillins. Ramsay (1957,p.514) indicated on a sketch-map the outcrops of the dykes of the Glenelg district, including some of Tertiary age. In the third edition of "The Tertiary Volcanic Districts" (British Regional Geology), which was first published in 1935, a summary of the main features of the Hebridean Swarms was again presented (Richey,1961,fig.2,pp.111-2).

Anderson and Dunham (1966) made considerable additions to the existing knowledge in a Survey Memoir of northern Skye. They stated that there is "a marked increase in the size, number and variety of the dykes as the Cuillin centre is approached and multiple and compound intrusions become more common" (1966,p.132). Their statement on the geographical behaviour of the size of the dykes, however, is questioned (Ch.9:II).

Anderson and Dunham (1966,pp.132-3,137) maintained that the majority of the most common group of dykes of northern Skye, viz. olivine-dolerites, belong to the last phase of minor intrusions and are frequently of later date than all the faulting. Those dykes of crinanitic and teschenitic affinities, on the other hand, all of which have geographically limited distributions, appeared to Anderson and Dunham (1966,p.91) to be of earlier emplacement and to be geographically related to corresponding groups of lava-types, each group of lavas being associated with its own centre of extrusion and distinguished on stratigraphic and petrographic grounds. These two authors even made so bold as to offer a possible order of intrusion of the basic dykes of northern Skye (1966,p.139), viz. 1. teschenitic dolerite, 2. olivine-dolerite, 3. crinanitic dolerite, 4. olivine-dolerite, 5. mugearite, 6. olivine-dolerite, 7. gabbro and allivalite, 8. olivine-dolerite.

Anderson and Dunham disagreed with Harker (1904) and Geikie (1897B) on the factors controlling the distribution of the dykes. Anderson and Dunham's view was that the degree of penetrability of a country-rock by a dyke is less dependent on the hardness of that rock than on the presence of pre-existing planes of weakness, e.g. bedding-planes, joints and faults, in that rock (1966,p.132).

Also in 1966, Bell (1966,p.339) located about 100 basic dykes in the Western Red Hills Complex, including one over 20m. wide. Brown and others (1969,pp.10-11) described, among other dykes, a problematic banded dyke in north-eastern Trotternish. But in general since 1966 increases in the knowledge of the dyke-swarms within the Area of Study have been of minor importance.

Chapter Three

GEOLOGY OF THE AREA OF STUDY

3:I. Introduction.

At the present surface of erosion of the dyke-swarms of Skye and Ardnamurchan it can readily be seen that the dykes intruded country-rocks of many different ages and types and possessing a variety of structural characters. The facet of the pre-Tertiary geology of greatest relevance to the present research is that which has been noted by many previous workers in the area, viz. the fact that the Tertiary dykes appear to be little influenced by, and generally (though not always) trend with marked discordance to, those pre-existing structures such as bedding, foliations, joints, and faults which are observable at the present day.

Fig. 4 shows the outcrops of the main lithological divisions in the Area of Study. (The geological boundaries shown in Fig. 4 are used in many of the illustrations in succeeding chapters.)

It is not the purpose of this thesis to present a detailed account of the known background geology of the Area of Study, except in so far as this geology can be shown to have affected the characteristics of the Tertiary dyke-swarms. The relevant details of such geological features are presented in the appropriate sections of the following chapters.

For descriptions of the pre- and post-Tertiary geology of the Area of Study, in some instances of wide-ranging and in other cases of narrow and specialized aspects, reference

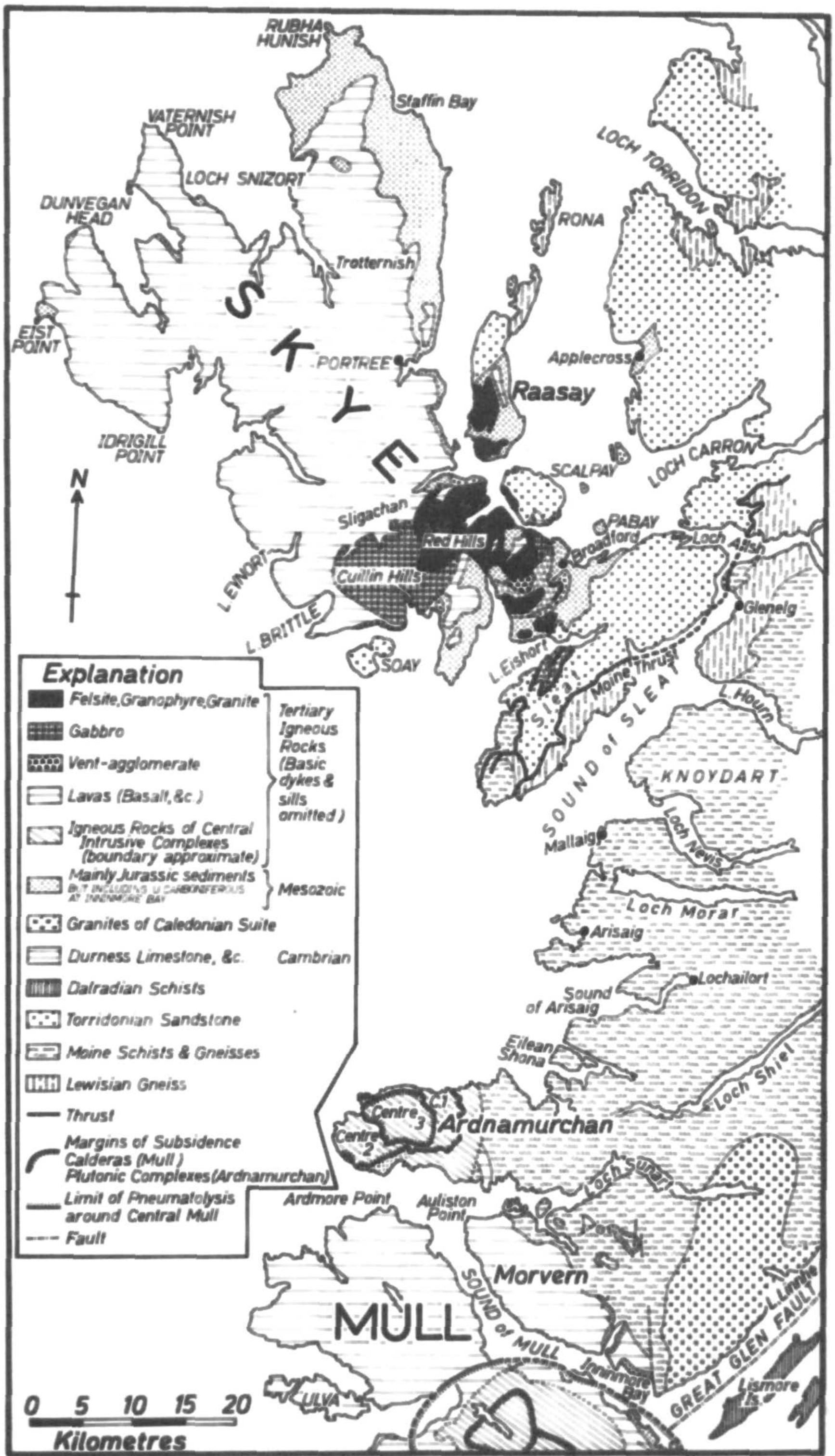


***Fig. 4.* Sketch-map of the Geology of North-western Scotland from Skye to Mull.** *(From the Geological Survey of Scotland and "Guide to the Geological Model of Ardnamurchan" (Mem. Geol. Surv.), 1934, Fig. 5.)*

must be made outside this present work to the writings of others (e.g. Harker,1904; Peach et al.,1907,1910; Lee,1920; Richey et al.,1930; Dearnley,1963; Watson,1965; M.R.W. Johnson,1965; Munro,1965).

The bulk of this chapter is devoted to geological descriptions of the lava-pile, Central Intrusive Complexes and sills of the Tertiary volcanic districts of Skye and Ardnamurchan, since the relationships of the dykes to these roughly contemporaneous extrusives and intrusives is of far greater significance than their relationships to other geological events. Previous to this, however, a few words are written on dykes of other ages than Tertiary outcropping in the Area of Study. The justification for the description here of such dykes is related to the obvious need to be able to distinguish in the field between them and the Tertiary dykes.

3:II. Dykes of Ages other than Tertiary.

In the Area of Study, dykes of other ages outcrop chiefly on the mainland (fig.5). Dykes of late-Lewisian age are found in Applecross (Lee,1920,p.60), with a few in south-eastern Skye (Clough in: Peach et al.,1910,pp.82-8). They are mainly basic and trend W.N.W.

Lamprophyre dykes of Caledonian age occur in the Glenelg-Knoydart and Moidart-Sunart regions, and trend east to west or towards W.N.W., with a few of north-easterly trend on the southern side of Loch Linnhe (these latter being part of the Ben Nevis Swarm).

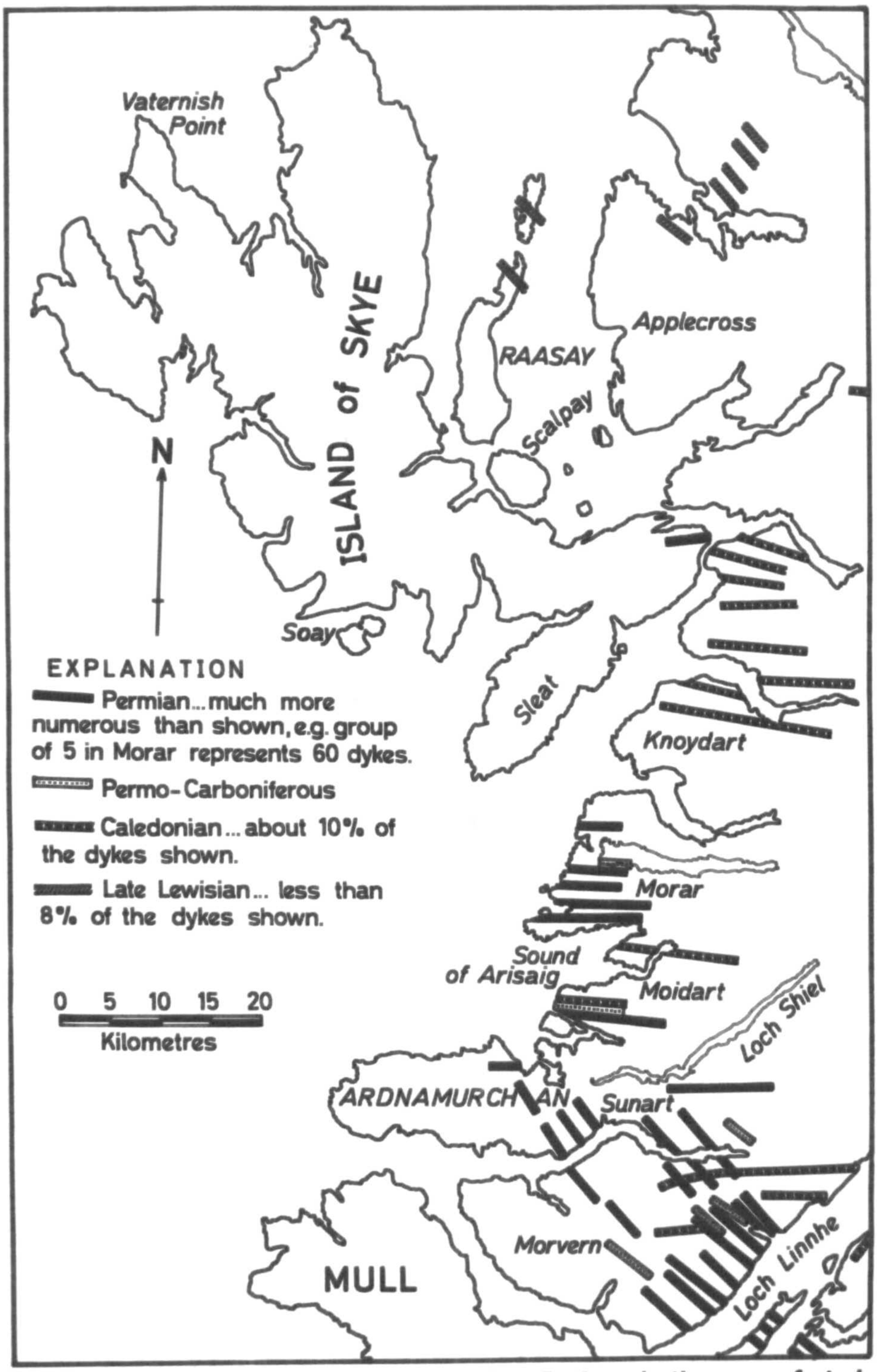


Fig. 5. Trends of dykes of ages other than Tertiary in the area of study (after J.E.Richey, The Dykes of Scotland, Trans. Edin. Geol. Soc., vol. xiii, part iv, 1939, figs. 1,2,4,and 5).

Lamprophyric dykes of Permian and Permo-Carboniferous suites outcrop in a belt from Morar to the southern limits of the Area of Study, and a few occur in south-eastern Skye (Clough in: Peach et al.,1910,p.87). In Morar, the Permian dykes trend east-west. From Sunart to Loch Linnhe both the Permian and Permo-Carboniferous suites trend W.N.W. (Appendix 26).

(Richey,1939,pp.397-400,402-19).

Scott (1928,p.158) stated that many N. to S. and N.W. Tertiary dykes follow the lines of earlier dykes and mineral veins in the Strontian district.

3:III. Tertiary Lavas and Sediments.

The plateau-lavas of the Tertiary Volcanic districts exposed at present in Co. Antrim, Mull, Morvern, and Skye, cover 5000 km^2. and consist mainly of an olivine-rich basalt which is occasionally crinanitic. Geikie (1897B) proposed that these and similar lavas exposed in the Faröes and older parts of the Icelandic platform are all that remains of a once very much larger field. On the other hand, because of differences in the petrology and sequences of the lavas in these volcanic districts, because of the discrete grouping of lavas near the Central Complexes, and because of the lack of large-scale Tertiary faulting to separate the supposed remnants of this large field, Anderson and Dunham (1966,p. 79) came to the conclusion that Geikie's notion is untenable.

The Tertiary lavas in Skye, which have a present areal exposure of over 1000 km^2, were extruded in conditions of an arid climate (Richey,1934,p.13), on to the peneplain of an eroded Jurassic syncline, and their base rests on different stratigraphical levels of the Jurassic and older systems. The volcanicity began explosively with subaqueous deposition of palagonite tuffs (G.V. Wilson,1937), volcanic dust, lapilli, and other ejectamenta from vents, along with freshwater shales and flags, in shallow freshwater lakes. At the same time some tholeiitic pillow-lavas were formed.

Later, in Skye, basic (mostly basaltic) and sub-basic lavas were extruded quietly to form a pile of more than 1200m. thickness. Anderson and Dunham (1966) concluded that the lavas in Skye were extruded "from local reservoirs developed as shallow offshoots from the main magma mass and subsequently becoming independent of it". They proposed that this main reservoir was in the form of an inverted V-shaped cleft, which passed beneath and parallel to the line of the east coast of Vaternish (1966,pp.90-1).

Between the extrusions of the various groups of lavas, explosive activity led to the accumulation of bedded tuffs and agglomerates. These intervening periods were also long enough for the formation of soils in some areas. Hawkes (1916) estimated a period of one-million years for the build -up of the Tertiary-pile in Iceland. A similar period is not unlikely in the Hebridean districts. The thickness of individual flows averages at about 6m. in Skye, although 15m. or more is not uncommon. The lateral spread of individual flows is of the order of several kilometres (Anderson & Dunham,1966,p.81).

The current view is that the lavas of Skye were extruded subaerially (except for the few tholeiitic pillow-lavas) from several fissures, each of which was active at different times. Each corresponding group of lavas thins away from the site of eruption, and meets and overlaps neighbouring groups. The result is an interleaved series in which early and late flows lie in juxtaposition (Anderson & Dunham,1966,p.79).

The collapse of the roof of the main magma chamber, according to Anderson and Dunham (1966,p.175), caused upward expulsion of the magma from the local reservoirs to form dykes. At the same time a shallow depression (basin) was formed in the lavas and crossed by N.W. and subsidiary N.E. sets of faults. Shallow folds were produced in the northwest of Skye, with their axes trending towards N.W., and these broke up the Jurassic folds into a series of domes.

Apart from local anomalies, the lavas of northern Skye and the similar lavas of Raasay have a westward dip. Estimation of the amount of dip is complicated by the block-faults which have an aggregate downthrow eastwards of some several hundred metres. Two parallel major faults with downthrow to the west (the Loch Greshornish Faults) are largely responsible for the preservation of the mugearite and trachyte lava-series in central-northern Skye (Anderson & Dunham,1966,p.176).

Harker (1904,p.6) considered that those lavas in Strathaird and immediately to the north and south of the Red Hills are fault-bounded remnants of a larger field, extending probably to cover most of southern Skye; they may also have extended much farther eastwards (Harker in: Peach et al., 1910, p.135) possibly to cover Raasay and Applecross (Judd,1874, p.254).

Anderson and Dunham (1966,pp.100-22) described the lavas of Skye in six petrographic types ranging from olivine-basalt to trachyte, the latter occurring only in small quantities.

The basalt lavas in Ardnamurchan —— all that remains of which is up to 90m. thickness — have been extensively removed by denudation (Richey,1934,p.9). The lavas rest on a widespread and thin basal deposit of mudstone (probably decomposed ash), suggesting to Richey (1934,p.15) that the pre-basaltic surface was a flat plain.

(Richey, Thomas, Bailey, & Simpson,1930,pp.103-18)

3:IV. Tertiary Central Intrusive Complexes.

Richey (1934,p.3) defined an intrusive complex of the Hebridean type as "made up of a number of intrusions which are arranged with reference to a common centre".

Richey (1932) pointed out that the major intrusive bodies of the Central Complex of Skye are disposed about three principal centres of activity, namely :-

(a.) Cuillin Hills,

(b.) Western Red Hills,

(c.) Eastern Red Hills.

(a.) Cuillin Centre.

The principal igneous bodies of the Cuillin Centre are the plutonic complex, the Coire Uaigneich granophyre, certain minor intrusions, and a group of pyroclastic rocks (Stewart,1965,pp.436-43).

The plutonic complex, composed of gabbros, eucrites, and ultrabasic rocks, was regarded by Harker (1904,p.85) as a series of laccolithic sheets — an idea first proposed by Forbes (1846). Richey (1932) and Bailey (1944,p.169) regarded the complex as a confluent cone-sheet complex. Recent work, however (Weedon,1961), has indicated that the plutonic complex consists of early ring-eucrites and unlayered gabbros "outside more than one set of later layered basic and ultrabasic cumulates, disturbed by arcuate fracturing involving subsidence and uplift, and associated with several steep eucrite intrusions" (Stewart,1965,pp.436-7). Their interpretation of the form of the layering of the inner and later group of gabbroic rocks led Wager and Brown (1968,p.409) to the conclusion that the various parts of the plutonic complex "belong, broadly, to a single episode of crystal accumulation within a basic magma chamber situated in the general position of the present complex". The ultrabasic rocks were not considered to represent a separate intrusion but were regarded as a series of crystal cumulates ending with the layered gabbros (Wager & Brown,1968,p.410; Weedon, 1965,p.66). The gabbros (sensu stricto) were intruded by the later ring-eucrites (Wager & Brown,1968,p.410).

The Coire Uaigneich granophyre forms a narrow strip intruding basalts and Mesozoic rocks not far outside the eastern margin of the gabbro of the Blaven range.

Closely associated with the major intrusions, not only in Skye but also in Rhum, Mull and Ardnamurchan, are enormous numbers of cone-sheets, which are commonly of quartz-dolerite, and less commonly of intermediate or acid rock. According to Harker (1904,pp.364-73) the sequence of minor intrusions in the Cuillins (with some overlap) is :-

(i.) Tangential basic dykes,

(ii.) Radial basic dykes,

(iii.) Cone-sheets,

(iv.) Radial ultrabasic dykes.

The cone-sheets are arranged concentrically about a point on the borders of the Western Red Hills "Granite" with the Cuillin "Gabbro", due north-east of the head of Loch Coruisk (Harker,1904,pp.366-9). The layering in the gabbros dips towards a similar central point (Richey,1961,p.90). Gibb (1968, p.412), however, noted that the ultrabasic dykes of the Cuillins and Strathaird focus elsewhere (on the Sgùrr Dubh ultrabasic body). Gibb also discovered that these dykes are not the latest intrusives but are sometimes cut by younger basic dykes.

The dykes of the Cuillins are of very basic composition, and the less basic types found in other parts of Skye are not represented (Harker,1904,p.364).

The pyroclastic rocks of the Cuillin Centre are composed of both very large agglomeratic bodies and many small patches found in the Cuillin Hills. The pyroclastic rocks are probably of several different ages, some being cut by cone-sheets and others not (Richey,1932).

(b.) Western Red Hills Centre.

Harker (1904) described the Western Red Hills as a composite laccolithic granitic body, composed of a number of sheets of different petrographic types and intrusive periods. Recent work by members of Oxford University, however, demonstrates that the complex consists of several acid bodies (granites, granophyres and microgranites) arranged in arcuate fashion centring near Loch Ainort (Stewart,1965,p.443). Brown (1963), Bell (1966), Wager et al. (1965), and R.N. Thompson (1969) believed that the separate epigranites of the Western Red Hills originated through partial melting, in the aureole of a large basic intrusion, of the Lewisian basement complex and possibly Torridonian sediments, with the possible addition of acid differentiate from the underlying gabbro. This hypothesis is supported by the strontium isotope abundance studies of Moorbath and Bell (1965) and lead isotope studies of Moorbath and Welke (1968A). Emplacement of granitic magma at higher levels may have been along ring-faults (R.N. Thompson,1969,p.373).

(c.) Eastern Red Hills Centre.

The almost circular boss-like mass of the Beinn na Caillich granophyre is apparently the latest major intrusion of the Eastern Red Hills, and it is possible that it fills a large vent of relatively late date (Stewart,1965,pp.443-5). Bordering Beinn na Caillich are various earlier, in some cases irregular sheet-like and in others steeply inclined arcuate, masses of gabbroic and granitic rocks, as well as some hybrid rocks containing partly digested gabbroic and granitic material in a basified granophyric matrix (Harker, 1896,1904; Stewart,1965,pp.443-5). The whole series of the Eastern Red Hills bodies intrudes country-rocks of Torridonian sandstone thrust over Durness limestone and dolomite, and of Mesozoic sediments. All of these country-rocks were later folded and faulted in a partly arcuate pattern around Beinn na Caillich (Stewart,1965,pp.443-4).

Anderson and Dunham (1966,p.175) referred to the Eastern

Red Hills as a series of boss-like intrusions, adding that the displacement of the Camasunary Fault by 5 or 6 miles (8km.) "suggests that the country-rock was literally forced apart to the full width of the intrusion". Indications to the south suggest that these displacements die out rapidly (to less than 1km. at the line of the Moine Thrust)(Anderson and Dunham,1966,p.175).

The "granite" (granophyre) bodies of Raasay are considered to be of sill-like form (Davidson,1935).

The igneous bodies of Ardnamurchan are concentrically disposed about three "intrusion-centres", and the plutonic masses constitute a ring-dyke complex (Richey,1934,p.5). Richey (1961,p.76) said: "Looked at in the broadest way, the complex may be regarded as a volcanic vent (represented by the vent-complex of Centre 1) pierced by two successive plugs (the ring-dykes complexes of Centres 2 and 3), with fringes of outwardly spreading sheets (cone-sheets) intruded at various times". The following sequence of events is observed :-

Ring Complex of Centre 1 : Volcanic vents including those of Ben Hiant were developed and were intersected by cone-sheets and major sheets, dykes and plugs of gabbro and granophyre, some of which are composite (Richey,1934,p.17; Richey, Thomas & Bailey,1930,pp.119-200; Stewart,1965,p.430).

Ring Complex of Centre 2 : The country-rock was domed before the intrusion of an outer set of cone-sheets, which in turn were followed by seven plutonic bodies (gabbros, granophyres and dolerites), followed later by an inner set of cone-sheets, and finally followed by four eucritic/gabbroic masses (Richey, Thomas & Bailey,1930,pp.119-40,173-281; Stewart,1965,pp.430-2 for summary). The plutonic bodies of Centre 2 are probably of ring-dyke form, although some may not be typical. Wells (1954), for example, described the Hypersthene gabbro of Ardnamurchan Point as a funnel-shaped intrusion. The form of this particular gabbro is still the subject of controversy (e.g. Skelhorn & Elwell,1971).

Ring Complex of Centre 3 : The complex has 15 main plutonic bodies (gabbros, eucrites, dolerites, tonalites, and monzonites), which are mostly of arcuate outcrop and of steep dip. Very few cone-sheets intruded Centre 3 (Stewart,1965, p.434). Wager and Brown (1968,p.504) gave evidence that the dips of the layering in the eucrite of Centre 3 is indicative of a lopolith or funnel-shaped intrusion, rather than a ring-dyke or series of ring-dykes.

3:V. Tertiary Sills.

Non-porphyritic and generally non-amygdaloidal dolerite/basalt sills were intruded chiefly into the Jurassic rocks of northern Skye and Raasay. Sills also occur to the south and east of the Central Complex of Skye, where they intrude

Torridonian strata, and in Ardnamurchan. In Raasay, the sills are picritic, crinanitic and teschenitic, with small syenitic segregations (Davidson,1935). Those of Harker's "Great Group of Basic Sills" of Skye which occur within the lavas (Harker, 1904,pp.235-53) are considered by later workers to be merely the central more massive parts of lava-flows (e.g. Anderson & Dunham,1966,p.80).

According to Anderson and Dunham (1966,p.125), the great sills of northern Skye, many of which are over 30m. in thickness, were intruded horizontally — at an isobaric level where the magma pressure was cancelled by the weight of the overlying rock. This, and the uniform aggregate thickness of the sills in any one area in northern Skye, point to a single source near the Cuillins. Anderson and Dunham (1966,p.175) stated that the Cuillin gabbro was probably emplaced contemporaneously with the dolerite sills, apparently at the same level. On the other hand, they pointed out that the distribution of the petrographic types of the sills corresponds to the distribution of the lava-types. In this case, lavas and sills being genetically related, the latter like the former may have been derived from multiple sources.

Among other minor groups of sills are: (i.) the narrow concordant sheets, intruded into the Torridonian strata of Soay, of similar porphyritic basalt to many of the dykes in that island (Harker,1904,pp.269-70); (ii.) the composite sills of the Eastern Red Hills Complex, intruded especially into Liassic country-rock, but essentially constituting an integral part of that Complex; (iii.) numerous small sills and sheets which are offshoots of the dykes of the regional linear-swarms of Skye and Ardnamurchan (Anderson & Dunham, 1966,p.132).

Chapter Four

NOMENCLATURE OF THE DYKES

4:I. Introduction.

Prerequisite to the understanding of a research-project of the type described in this thesis are certain preconceived ideas of what a dyke and a dyke-swarm are. Many such notions obviously derive from a study of the researches and definitions of earlier workers.

The aim of the research is to determine the form and structure of certain Tertiary swarms and to arrive ultimately at some conclusion as to their genesis. By this means, a comprehensive definition of these particular swarms is acquired, and the preconceived ideas are accordingly modified. The same argument applies to the definition of the term "dyke". An attempt is made in this chapter to give a representative review of the definitions and ideas offered by earlier workers, and to explain any adjustments of these required to establish a set of criteria which are suited to the description of the dykes and dyke-swarms of Skye and Ardnamurchan.

4:II. Dyke.

A dyke, which is variously described as tabular, sheet-like, plate-like, or wall-like, is a vertical or steeply dipping, discordant, intrusive body, which has nearly or quite parallel marginal walls and is narrow in proportion to its outcropping length (Geikie,1923,pp.738-9,743; J.W. Miller, 1925,p.140; Tyrrell,1931,p.202; Daly,1933,p.90; Harker,1941, p.120; Umbgrove,1950,pp.117-8; Field,1951,p.16; Fletcher &

Wolfe,1953,p.234; Billings,1954,p.307; Longwell & Flint,1955, p.32; H.D. Thompson,1960,p.298; Turner & Verhoogen,1960,p.66; Hatch et al.,1961,p.139; Read & Watson,1962,p.367,and 1966, p.45; Mather,1964,p.31; Holmes,1965,p.249).

Not all authors agree upon the steep inclination of dykes, although Lyell (1885,pp.6-7) went so far as to imply that dykes are strictly perpendicular (meaning vertical). Daly (1933,p.90) said that dykes have any angle of dip and that "some dykes with low dips are hard to distinguish from sills moderately transgressive among flat-lying sediments". Gilbert (1939,p.593) was of a similar opinion to Daly. Clough and Harker (1899,p.382) noticed a sub-horizontal basic sheet which along its outcrop assumed a "vertical dyke-like form". Geikie (1889,pp.45 & 139) described the most shallowly dipping dykes as "those which occur in the basalt-plateaux of the Inner Hebrides, where the same dyke in some parts of its course runs horizontally between two beds, across which it also ascends vertically".

Dips of as low as 20 deg. are recorded at the outcrops of Tertiary dykes in the Area of Study (Ch.10:II). Such dykes behave in a manner similar to that described by Geikie, with both shallow and steeply inclined portions along their strike. If such a dyke is of extremely shallow dip for most of its observed length of outcrop, and steeply inclined along a small portion only, then its characteristic inclination is the lower angle and this is the value recorded (Ch.10:II; Appendix 16).

Where the dyke invaded a country-rock which is not massive or structureless, it is generally held that the dyke should have cut across the bedding or other foliation, i.e. is discordant. Again, Geikie (1923,pp.738-9) said that dykes may follow highly-inclined stratification, and as such "they look like interstratified beds, though really intrusive". Once more the present author can only agree with Geikie. In the Morar districts, where the foliation of the Moinian psammites is steep, intrusive sheets are often concordant (Ch.6:VI). Such sheets have an intensity-distribution which is entirely in accord with the distribution in adjacent areas of undoubted discordant dykes (Ch.6,7,8), and hence can only be dykes themselves.

It is almost unanimously agreed that dykes by definition have an intrusive nature. Billings (1954,p.307) said, "Some bodies that appear to be dikes have been formed by metasomatic replacement", and she referred to the field-characters and petrographic criteria of Goodspeed (1940,pp.194-5), which facilitate distinction between truly magmatic dykes and metasomatic tabular bodies.

A few authors have attempted to define the dimensions of dykes. A breadth of less than one-inch to several hundred feet was proposed by J.W. Miller (1925,p.140) and

H.D. Thompson (1960,p.298). Zumberge (1958,p.44) described the range of thickness of dykes as from a few inches to over 100 feet. J.W. Miller (1925,p.140) stated that their outcrop-length is from a few feet to 20 miles or more. The distinction between dykes and veins, the latter being generally much narrower and commonly products of metasomatic replacement or hydrothermal processes, was more precisely defined by Geikie (1923,p.744), who said that dykes "differ from veins in the greater parallelism of their sides, their verticality, and their greater regularity of breadth and persistence of direction".

Ideally, the definition of a dyke must be genetic. However, there are divergent opinions on the origin of dykes. Billings (1954,p.307) adequately stated the two extreme views, when she said of the walls of a dyke that they "may be pushed apart by the pressure exerted by the intruding magma, or the magma may quietly well up into fractures opened by tensional forces". In favour of the former, active mechanism of intrusion were, for example, M. Smith (1965, p.102) and Read and Watson (1962,p.367), although Read and Watson (1966,p.45) also said that dykes are "formed by magma filling fractures opened by tangential tensions in the crust". M.Smith (1965,p.102) said that dykes "have taken advantage of joints or fractures within the sediments, the magma having forced the sides apart". Billings (1954,p.309) agreed that dykes "may occupy very much earlier joints or fractures". In favour, on the other hand, of the passive mechanism were Phillips (1885,p.334), Geikie (1923,pp.738-9), J.W. Miller (1925,p.140), Lake and Rastall (1941,p.13), Gilluly et al. (1951,p.79), Zumberge (1958,p.44), H.D. Thompson (1960,p.298), Holmes (1965,p.249), and Robson (1968, p.48).

The present author believes that, although a genetic classification of tabular bodies into dykes, sheets, or sills is an ideal to be striven for, such definitions are attended by so many difficulties that it is impracticable to attempt to formulate them here, although Chapter 16 constitutes what is in effect a formulation of a genetic definition of a Tertiary Hebridean dyke.

4:III. Simple and Multiple Dykes.

A simple dyke is "the result of a single intrusion of magma" (Billings,1954,p.307). Multiple-dykes "represent a history of repeated intrusions, into the same fissure, of material of similar composition" (Robson,1968,p.48). Authors are generally agreed that the successively intruded component dykes of a multiple-intrusion must be of a similar composition (e.g. Daly,1933,p.91; Billings,1954,p.307; Hatch et al.,1961,p.141), although Geikie (1923,p.746) said that a multiple-dyke is simply "formed by more than one intrusion of molten material" by reopening of the same fissure. Harker

(1941,p.123) held a similar view to Geikie.

The author, like Geikie, believes that all that is required of a multiple-dyke is that the later components are chilled against earlier ones, and that compositional similarities among these components constitute an unnecessary adjunct.

4:IV. Composite Dykes.

Daly (1933,p.91) said that composite dykes are "formed by successive injections of chemically differing melts into the same fissure which widens to receive them". Although not as specific as Daly in their views on the mechanism of origin, Harker (1941,p.119), Billings (1954,p.307), Hatch et al. (1961,p.141), and Robson (1968,p.48) agreed that the components of a composite dyke are chemically different.

The present author agrees with Walker and Skelhorn (1966,p.96), who said that "the acid and basic components appear to have existed as separate magmas before coming together" to form such bodies as composite dykes. These authors added that the junctions between the earlier-intruded basic margins and the later central acid component are sharp, and that sometimes, where the basic magma had not completed its crystallization before the intrusion of the cooler acid magma, the former may be chilled against the latter.

4:V. Dyke-Swarm.

Muff (in Peach et al.,1909,p.82) was the first to recognize a confocal relationship between a linear dyke-swarm and a central plutonic complex (in Mull). Suess (1909, vol. iv., p.572) said that "a whole network of dykes may be present in the neighbourhood of a volcano". Tyrrell (1931,p. 202) wrote that in an assemblage of dykes (a swarm) the dykes "may be all parallel to one direction, or may be radial to a centre". Daly (1933,p.94), Harker (1941,p.120), and Read and Watson (1966,p.45) concurred that the distribution of the trends of the dykes constitutes the most important criterion for the recognition of a swarm, and added that a swarm is made up of large numbers of dykes.

Read and Watson (1962,p.399) stated that dyke-swarms "are often centred about larger intrusions, especially about ring complexes", and that the patterns of the swarms "are determined by magmatic pressures or by earth-movements" (1962,p.395). Gilluly and others (1951,p.450) wrote of dyke-swarms that "some, especially radial swarms, are related to volcanoes; others are offshoots of large plutonic masses deep beneath the surface; others appear to have been feeders for plateau basalts, and others for sill complexes, lopoliths, or other igneous masses".

The author feels that necessary additions to the definitions of other writers are (i.) that the dykes of a swarm were intruded during the same general period of igneous activity, and (ii.) that the intrusions are confined within a region of definable extent.

4:VI. Regional Dyke-Swarm.

The distinction between a dyke-swarm and a regional dyke-swarm is not precise. It is largely dependent upon the numbers of dykes and the area occupied by their outcrops. Hills (1963,p.377) said that dykes "rarely occur alone, but are commonly grouped in dyke swarms consisting of hundreds or thousands of individual dykes, and, in regional swarms, extending for tens or hundreds of miles". Billings (1954) and M. Smith (1965,p.102) held similar views, although the former went a stage further. Billings (1954,pp.307-9) defined a "dyke-set" as a system of parallel dykes, and added that in some districts "several sets may be present, and each may be characterized by its own peculiar petrography, indicating that the various sets are of different ages". Hills (1963,p.377) argued that regional swarms "are related to major crustal structures and stresses".

In this thesis it is suggested that in the Area of Study there are sufficient numbers of dykes in a large enough area to constitute at least three regional swarms (Skye, Ardnamurchan, and the Small Isles — see also XIII, below). The author does not see the necessity at this early stage in the discussion for a genetic definition of a regional swarm.

4:VII. Linear Dyke-Swarm.

The classification of swarms into linear, radial, concentric, and tangential types is founded largely on an interpretation of the characteristics of the trends of the individual dykes.

A linear dyke-swarm is constituted by numerous and closely spaced parallel dykes (Longwell et al.,1948,p.286; Kirkaldy,1954,p.32). In practice, the dykes of all linear-swarms are sub-parallel. To define the limits of variability of trend allowed for by the noncommittal term "sub-parallel", a knowledge of the variation on a geographical basis is required. Such variations of trend are obviously unique to a particular swarm (Ch.6).

4:VIII. Radial Dyke-Swarm.

Hills (1963,p.377) defined "local dyke-swarms" as "swarms localized about volcanic centres or in the neighbourhood of stock-like intrusions". He added that such swarms are "commonly radial in pattern, and centred on the volcanic neck or stock" and that "where the local geology is complex the radial pattern may be modified", as in the swarms of the Spanish Peaks (R.B. Johnson,1961). Many authors believe that radial-swarms are always related to a central volcano or vent (Mallet,1876,p.491; Tyrrell,1931,p.202; Longwell et al.,1948,p.286; Gilluly et al.,1951,pp.439-40; Billings,1954,p.309), and some examples of such a relationship were described by Iddings (in Wolff,1892,p.451), Iddings (1893), Weed and Pirsson (1895,p.399). Holmes (1965, p.260) believed that "radially arranged dykes fill tension fractures produced by the updoming of the roof rocks above an expanding diapiric igneous intrusion".

The opinion of the present author is that radial dyke-swarms can be defined on a simple basis only, viz. the dykes are so distributed in space that the trend of each forms part of a radius of a circle.

4:IX. Concentric Dyke-Swarm.

The trend of each dyke of a concentric-swarm is simply concentric to a particular point. Theoretically such a dyke has an outcrop curving along the arc of a circle, the radius of which is the distance of the dyke-outcrop from the central point (Kuenen,1945,p.18). Sloan (1970,pp.88-93) has demonstrated the existence of such a concentric cluster of dykes in Croggan, Isle of Mull.

4:X. Tangential Dyke-Swarm.

The dykes of a tangential-swarm lie along the tangents to concentric circles. Such dykes are straight or they curve away from the centre of these concentric circles (Kuenen, 1945,p.18). Like concentric dyke-swarms, tangential-swarms are often localized within certain sectors. Clearly, to distinguish between concentric and tangential dykes it is necessary to trace their outcrops and study their geometry, although this may obviously be difficult or impossible in certain cases where the necessary exposures are poor or lacking.

4:XI. Secondary-Swarm.

Within a regional linear dyke-swarm, in addition to a major axis of high-intensity of dykes, a second parallel axis of less high intensity may be found. Intervening between these two belts of high-intensity there must of course be a region of intensity lower than on either side. In this thesis the axis of less high intensity (subordinate to the major axis) is called an axis of a secondary-swarm (Ch.7: VI,a).

4:XII. Subswarm.

In the present work the dykes of subswarms are defined as those of trends which are characteristically different from those of the major and secondary, linear, N.N.W. swarms. Generally, a subswarm is also of linear type, e.g. the minor N.E. swarms of Skye (Ch.6:IV), but is usually less extensive than the regional linear-swarm with which it is associated, and in relation to which it is thus aptly designated as subsidiary (Ch.7:V). The term "linear-swarm", however, is generally restricted in its usage in this thesis to the regional linear dyke-swarm of N.N.W. dykes.

4:XIII. The Use of the Terms "Skye-Swarm","Ardnamurchan-Swarm", etc.

A regional linear-swarm of N.N.W. dykes extends from Skye southwards towards Mull. The intensity of this swarm decreases away from the Central Intrusive Complex of Skye and in Sunart (fig.3) increases again towards the Central Intrusive Complex of Mull (Ch.7&8). Along the lines of minimal intensity of the dykes between these two Central Complexes a geographic boundary is drawn between the "Skye-Swarm" and the "Mull-Swarm". A similar procedure is used to define the geographic limits of other swarms in the Area of Study.

The terms "Skye-Swarm", "Ardnamurchan-Swarm", etc., are largely of geographical character, and as such they have little scientific merit. In one sense they may even be misleading, for they may draw too precise a boundary within what is in fact an indivisible system of dykes with close structural and genetic connexions. Yet the terms prove to be of great convenience for the purpose of analysis of the characters of the Tertiary Hebridean dykes.

The term "Skye-Swarm" is sometimes used in this work loosely to signify incorporation of, not only the dykes of the regional linear-swarm of N.N.W. dykes, but also the sub-swarms lying in the area demarcated in the manner described above.

4:XIV. Dyke-Complex and Rift Zone.

According to Wentworth and MacDonald (1953,p.89), a dyke-complex (in Hawaii) represents recurrent intrusion of dykes in parallel or subparallel pattern along the line of a "rift zone" (see below). The frequency of the dykes falls off rapidly outside the limits of the dyke-complex proper. An intensity of 100 dykes per mile (about 60 per km.) can be taken as the definition of the lower limit, although at higher levels in a fissure-fed lava-pile this lower limit may fall to 10 dykes per mile.

Rift zones (Wentworth & MacDonald,1953,p.11) intersect the flanks of shield volcanoes in Hawaii. They are zones of fracturing from which fissure-fed lavas arise. Grabens may lie along parts of these. Rift zones in Hawaii vary from a few hundred feet to 2 miles in width. On the basis of the observed patterns of the rifts in Hawaii, Wentworth and MacDonald (1953,p.14) attributed the origin of these zones to the pressure of magma below the volcano. If this pressure exceeds the weight of the overlying rocks, the upward thrust beneath the summit of the volcano would be expected to produce three principal radiating rifts, two of these better developed than the third because of the non-homogeneous structure of the volcano.

In Chapter 16 reference is made to zones of rifting. Rifting in that sense signifies the separation of crustal plates via the process of ocean-floor spreading.

Chapter Five

THE METHOD OF STUDY

5:I. Introduction.

The configuration of the present-day exposure of the dyke-swarms of Skye and Ardnamurchan can be regarded in the simplest sense as a plane. In reality, the distribution of the dykes is a four-dimensional function. The dykes extend to a depth below (and originally to some height above) the length and breadth of the plane of the outcrop at the present level of erosion. The time-interval, during which the dykes were intruded, constitutes the fourth dimension.

A study of the dyke-swarms in depth might be a feasible proposition in an area with extremes of topographic relief. Unfortunately, such extremes in the Area of Study are found only in the vicinity of the Central Intrusive Complexes, e.g. in the Cuillin Hills. The evolution of the dyke-swarms through time is of fundamental importance, but the elucidation of such is attended by various problems. Cross-cutting or chilling relationships between dykes give some evidence of relative ages, but such observed relationships are rare compared with the total numbers of dykes recorded, because of (i.) the lack of exposure, and (ii.) the lack of time to trace individual dykes across country to localities where more examples of these phenomena could possibly be observed. Alternatively, isotopic-dating methods, if precise enough, would be a suitable means to analyse the age-relationships within the dykes of the swarms. Restrictions to the solutions of the questions of the time-relatioships, etc., seem inevitable, but attempts are made wherever possible to overcome these. In essence, the problem is reduced, prima facie, to a study of the areal distribution of the swarms.

Attempts to achieve an analysis of the form and structure of the swarms in a two-dimensional plane necessitate the location of some fraction of the total assemblage of dykes, along a number of selected "lines" within the "plane" of the present land-surface. In effect, the outcrop of a single dyke then becomes a point on a line of section within this plane. At each point the corresponding dyke has the property of position within the plane, and the associated functions of its trend, thickness and dip at that locality. What proportion of the total assemblage is constituted by the dykes in these sections or traverses is an unknown factor. To speak of an exact fraction of the total involves arguments not only about the finite length of a dyke, and correlation from one section to another between outcrops of the same dyke, but also its depth, or rather the height to which it reaches from the supposed source at depth. These arguments cannot be resolved with any certainty, largely because of the lack of exposure. Consequently, it is somewhat illogical to talk of a fraction of the total number of dykes. The point for emphasis is that the whole of the area is not studied in detail. Indeed, individual dykes are very rarely traceable across country. Moreover, the selection of traverses is largely limited to those which are well-exposed and which lie approximately at right-angles to the dominant trend of the dykes.

5:II. A Possible Method of Analysis of the Data.

A brief discussion follows of perhaps one of the most logical of the possible schemes of analysis. For reasons given later, certain parts of this scheme are adopted, whereas other parts are omitted.

The position of an individual dyke as a point-spot in a plane can be located with reference to a grid with axes at right-angles (square-net), e.g. the National Grid. Alternatively, the position can be located on a circular-net; a point-spot then possesses two functions, (i.) the distance to a central-point, i.e. the centre of the net, and (ii.) the angular-bearing to that point, i.e. with reference to some base-line, e.g. the north-south meridian. The most suitable arrangement of such a net is that in which its centre coincides with some focal-point on which the intensities or trends of the dykes converge.

Deferring for the moment such variables as the petrology, the chemistry, the age, the length, and the height (i.e. the distance from the source to the original, pre-erosion, termination) of the dykes exposed at present there remain the variables of position, trend, dip, and thickness of the dykes. The simplest treatment of the recordings of trend, dip and thickness is by univariant analysis of each of these functions. This constitutes an initial, simple, but nevertheless valuable approach to the problem. The frequency-distribution of these functions can involve the total number of dyke-outcrops observed, or it can relate to small groups of dykes outcropping in distinct areas. Any variation in the character of the three functions from one small group to the next may obviously be of some significance.

Using the method by which the dykes are located on a circular-net, nine rational bivariant analyses of the five simple variables — distance to centre of net, angular-bearing to centre of net, trend of dyke, dip of dyke, and thickness of dyke — are apparent:-

(a.) Distance to centre vs. trend;
(b.) " " " vs. dip;
(c.) " " " vs. thickness;
(d.) Angular-bearing to centre vs. trend;
(e.) " " " " vs. dip;
(f.) " " " " vs. thickness;
(g.) Trend vs. dip;
(h.) Trend vs. thickness;
(i.) Thickness vs. dip.

The tenth possible bivariant analysis, distance to centre vs. angular-bearing to centre, is, of course, extraneous.

The ideal position of the centre of the net is at a point in the same vertical line as some focal-point of activity, this activity relating directly to the form, the distribution and the genesis of the dykes of a swarm under consideration, e.g. the Skye-Swarm. As suggested above, a convergence of the trends of, or distribution of the intensities of, the dykes might indicate the whereabouts of such a point. However, a means, independent of those functions which are to be analysed, of location of the focal-point is preferable. For example, the centre of the net for the analysis of the properties of the dykes of the Skye-Swarm could be made coincident with the site of the maximum Bouguer anomaly, which lies within the Cuillins (McQuillin & Tuson,1963), since this may be considered to overlie the axis of that cylinder of basic material proposed by McQuillin and Tuson (Ch.12:III).

Unfortunately, certain sectors and rings in this proposed net are lacking in exposures and consequently in recordings of the dykes. Exposure is limited, for example, in south-western sectors in Skye, where the sea encroaches close to the Cuillin Gabbro, and in almost all sectors and rings about a similarly designated central-point in Ardnamurchan. Other sectors and rings are simply poorly-exposed.

Whatever the reason, the resulting unequal distribution of the data leads to anomalous comparisons of the properties of the dykes of one sector with those of another sector, or those of one ring with those of another ring.

Because of the far from uniform distribution of the dykes, the graphical plots for bivariant analyses a. to f. cannot be interpreted as normal density-plots, but could be treated as axial-plots. For example, the most common value of the trend of the dykes (in say a 10-deg. range) in each of several rings could be calculated. This value may change systematically from one ring to another outwards from the centre of the net. Connexion of these maxima would give an axial-plot showing the change in the trend with distance from the centre of the net. The analyses, indeed, need not be restricted to whole rings, but the area may first be divided into quadrants, and so on, and the change in the character of certain functions with distance from the centre of the net in each of these subdivided regions may be analysed by the use of the same equal-interval rings.

Further to the problem of the lack of exposure, the question of the variability of the country-rock within those rings and sectors which are reasonably well-exposed also arises. It is evident if one sector, for example, contains within it dykes which vary significantly from one rock-type to another, e.g. orientation of bedding or foliation, nature of folding, fault-patterns, joint-systems, elasticity, etc., that anomalies can arise within this sector because of the influence of the form of the country-rock upon the properties of the dykes.

There are, nevertheless, certain advantages to the application of the method described above. Approaches towards a radial or concentric disposition about the central-point of the values of the trend, dip or thickness of the dykes can be readily ascertained. The majority of the dykes, however, belong to linear-swarms, and for purposes of analysis the Area of Study might more suitably be divided into either (i.) equal-width, parallel strips trending towards N.W. or N.N.W., as did Tyrrell (1928) for the dykes of Arran, or (ii.) into equal-area squares. The disadvantages of these two methods are that again the numbers of recordings vary appreciably from one division to another, and the strips transgress areas of widely varying background geology.

Experience of the difficulties involved in the use of circular-, square-, and strip-, nets has prompted the author to adopt an approach to the problems of analytical technique which is described below under the head, "Method Used".

5:III. Method Used.

It appears that the separation of the dykes into groups for the purposes of analysis cannot be too rigidly mathematical. Undoubtedly, the investigation of the form and structure of a dyke-swarm demands a certain degree of logicality of approach, and yet application of purely statistical methods seems, for one reason or another, to be inadequate. Separation of the observed dykes into some form of grouping is inevitable, for it is required for assessment of the variation throughout the Area of Study of their properties.

Computation of an arithmetic-average value of trend, for example, on the measurements of a number of dykes sufficiently large to be of statistical validity, leads to geological impracticalities. The areal-extent, within which such large numbers of documented dykes outcrop, often covers localities of widely differing background geology. Moreover, the number of such groups, each of a large number of dykes, is small, and the probability of exhibiting systematic variations in the properties of the members of the swarms, on a regional basis, is reduced. Lastly, and not to be judged too lightly, are the questions of the ease of handling of the data and the clarity of its presentation.

In order to strike a balance between the two apparently opposing factors of statistical and geological validities, a separation of the recorded dykes of the regional linear N.N.W. swarms into groups of 100 seems in practice to be a satisfactory solution. However, in districts where few readings are available, either because of the low numbers of dykes, or because of poor exposure, the area encompassing the sections in which the outcrops of 100 dykes are located is from a geological viewpoint too large. In such cases groups of 50 dykes are used. This forms the major inconsistency in this method of analytical approach, but it is unfortunately unavoidable. The results of analyses on this basis, seen in later chapters, are sufficient to repudiate any doubts which may arise.

Fig.139 (Appendix 25) illustrates the locations of all the traverses covered in the Area of Study. Fig.6 (in pocket) is a map showing the sections of shore, stream, cliff, etc., along which the outcrops of the dykes constituting each group (for the swarms of Skye and Ardnamurchan only) are located. It must be emphasized that the groups of 100 and of 50 dykes are made up from members of the regional linear-swarms of N.N.W. dykes. The subswarms are analyzed separately. For the regional linear-swarms of Skye and Ardnamurchan there are a total of 74 groups: 43 of 100 dykes, and 31 of 50 dykes. Each group of dykes has a code-number and a code-name (e.g. Appendix 3). The code-name is simply a prominent locality within the area containing those sections from which a group of dykes is assembled.

The code-numbers of the groups are shown on the map (fig.6). The numbers refer to groups of 100 dykes, e.g.

"20", "35", etc. Groups of 100 dykes are located on Skye and the adjacent islands. Numbers suffixed by a letter of the alphabet, e.g. "4A", "5B", "19A", etc., refer to groups of 50 dykes. Such groups as these are located in northern Skye and south of the Cuillins. (The small number of recordings on Harris precludes the compilation of a group.)

Elsewhere, codes consisting of letters of the alphabet only are used. Except for "OA" and "OB" which represent groups of 50 dykes on Raasay and western Soay, respectively, all other groups prefixed by the letter "O" (i.e. from "OC" to "OR") are located on the mainland, and are also groups of 50 dykes. On the mainland the intensity of the dykes is low, and the outcrops of groups of 100 dykes would encompass an area too large to be practical. Finally, codes prefixed by the letter "A", e.g. "AC", refer to groups of 50 dykes on the Peninsula of Ardnamurchan.

By no means all of the dykes recorded are used to establish these groups. In some cases, for example on a small island, perhaps 20 dykes over and above the required number to set up a group, are documented. And yet, the island may be too remote from any other area for the possibility of using these 20 dykes in the compilation of another group. By the same token, the sections shown on fig.6 by no means represent the total traverses covered.

Despite the use of such low numbers of dykes as 100 or

50, there remain some anomalies. In certain groups, even of such low numbers, data is derived from dykes of different rock-types, of some range in age, and which outcrop in widely different country-rocks (compare figs.6 & 4). One additional problem is that the location of a centre-spot for a group of dykes is somewhat vague in groups made-up of dykes outcropping in sections covering a wide area. Fig. 7 is a map showing the point-spot centres for the 74 groups. The purpose of defining such centres is to allow allocation of average values of the properties of the dykes, e.g. average thickness, to such positions, with the result that the distributions of such properties can be contoured.

The advantages of a method employing groups of 100 or 50 dykes are (i.) that it can be used throughout the analyses of the various functions, e.g. arithmetic-average trend, standard-deviation of trend, geometric-mean thickness, and so on, (ii.) the ease of handling such even numbers, and (iii.) the dissuasion from arranging the groups for the analysis of one property, e.g. arithmetic-average trend, differently for the analysis of some other property, e.g. arithmetic-average thickness. On this last point, it may be noted that the groups are established with no prior thought as to what use they may be in illustrating any one particular aspect of the dyke-swarms. Their establishment is merely governed by the available exposure or intensity

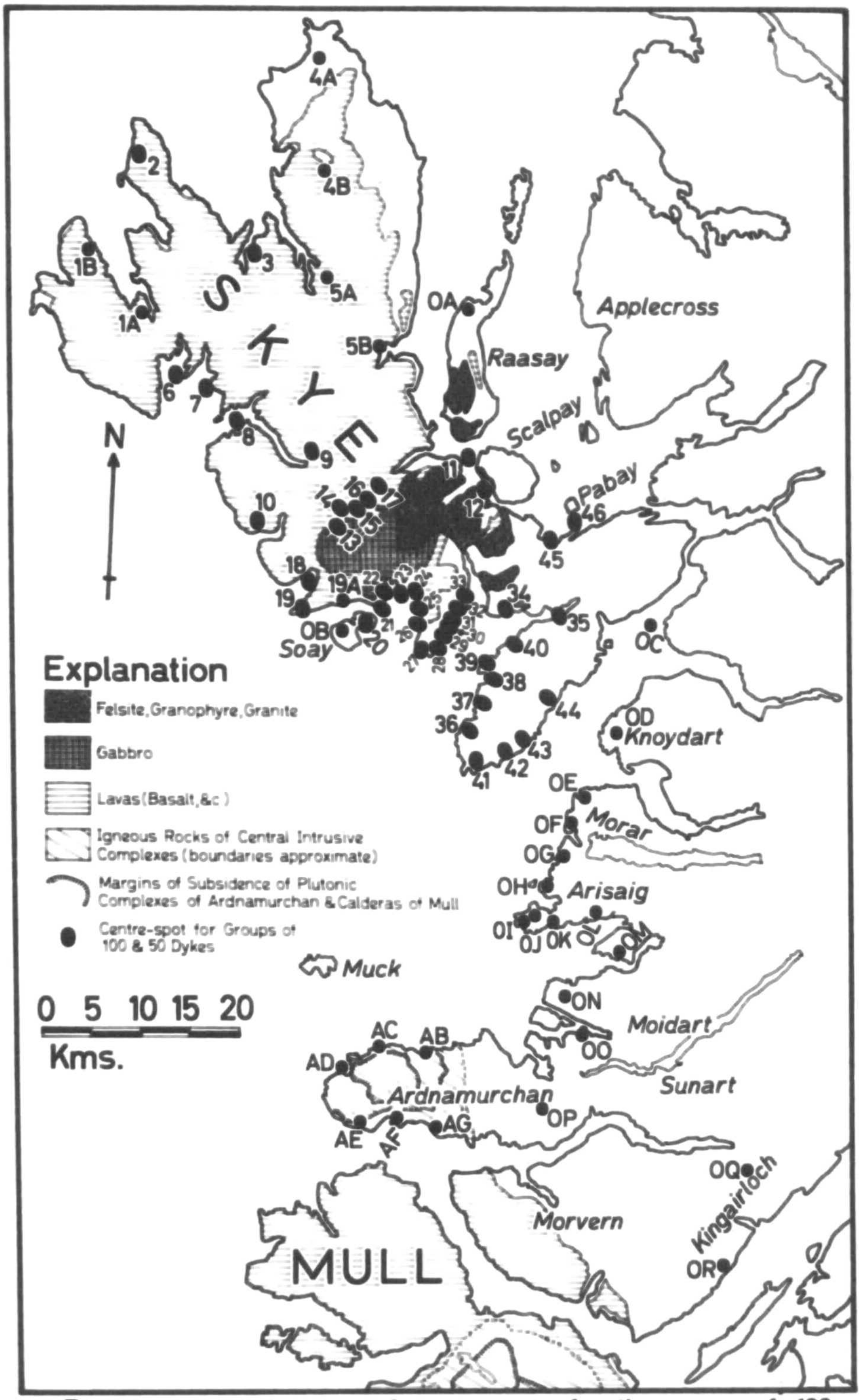


Fig. 7. Map showing locations of centre-spots for the groups of 100 and groups of 50 dykes, each with its code. Some of the Tertiary igneous geology also indicated.

of the distribution of the dykes in particular areas, and is otherwise perfectly random.

There arises a problem which hinges on the bias of mapping on coasts at right-angles to the main trend of the regional linear-swarm. This increases the probability of neglect of dykes of trend other than roughly north-west, e.g. north-easterly trending dykes. However, no dyke of unusual trend is disregarded. Both its significance as an individual, i.e. with regard to possible very localized controls, and its significance on a wider scale, i.e. with regard to the possibility that it may be a member of a sub-swarm, are considered. In any district where for instance north-easterly trending dykes are found during the course of mapping, attempts are made, where exposure permits and where access can be gained, to determine by searching along north-west to south-east trending sections whether other dykes of the same trend are congregated in that locality.

In summary, it is apparent, and will become more so in following chapters, that the various properties of individual dykes, e.g. trend, dip, thickness, etc., are best analysed by using small groups of 100 or 50 dykes. The study of the variations of such properties as arithmetic-means, medians and geometric-means of trend and thickness then follows a simple and consistent procedure. Similar remarks apply to the studies of (i.) the frequency-distributions of trend, dip and thickness in these groups, (ii.) the geographical distribution of dykes within certain ranges of trend, dip, or thickness, (iii.) the standard-deviation of the trend, (iv.) the average angle of dip of the dykes, and (v.) the geographical distribution of multiple-intrusions. In many cases the variations of these functions can be represented by contouring.

Facets of the work which are not, or at least less, affected by the subdivision into groups include (i.) analyses in certain localities of the controls on the trends of the dykes by the country-rocks, e.g. through joints or foliation, (ii.) distinction of subswarms on the basis of trend, (iii.) calculation of the regional variation of crustal-extension (dilation) due to dyke-emplacement, and separation of linear-swarms on this basis, and (iv.) calculation of the variation in the intensity of the dykes as the function, the number of dykes per kilometre.

5:IV. Dykes Excluded from the Analyses.

In Skye, at least, felsite, granophyre and composite dykes are of an earlier date than the majority of the basic dykes, and their origin is linked with the "granite" bodies of the Central Intrusive Complex (Harker,1904,pp.197-290). Moreover, the group of minor basic intrusions, related to the Cuillin Gabbro and scarcely occurring beyond the limits of its outcrop, and a small group of late, radially-disposed peridotites restricted to the Cuillins and north-western Strathaird (Harker,1904,pp.364-6, and pp.374-80; also Ch.3: IV,a), are both likewise related to the local rather than the regional controls. On the other hand, certain pitch-stone dykes and some localized groups of intermediate types, which are not at least related to the Central Complex in the same manner as the above groups, are considered here to be members of the regional-swarm of basic dykes.

Because of their limited distributions and numbers, the dykes of the Cuillins, and the acid, composite, and so-called (Ch.3:IV,a) late peridotite dykes, are very infrequently met with in those sections traversed. Consequent upon this and upon considerations of their different mechanisms of formation, such dykes of local types are excluded from the analyses described in the following chapters. For the sake of consistency, the acid dykes of the Ardnamurchan Peninsula, similarly few in number and probably again of local character, are also excluded.

5:V. Concluding Remarks.

The following seven chapters contain a largely descriptive analysis of some properties of the dykes and the dyke-swarms. All of these properties are at least in some small way inter-related, but for the sake of clarity such correlations and their significance are largely postponed until an examination of them is made in a summary-chapter

(Ch.13).

As a postscript and in parenthesis, it must be emphasized that less than 20 dykes are recorded along sections studied in Harris. This being too small a number to constitute a group, the island is omitted from maps illustrating the results of analyses using the 74 groups.

Chapter Six

THE TRENDS OF THE DYKES

6:I. Introduction.

The distinction between different types of dyke-swarms, e.g. linear, radial, etc., is based chiefly on an interpretation of the trends of, and to some extent on the distribution of the intensities of, the constituent dykes.

Earlier workers have described the major variations in the trends of the Tertiary dykes of the Skye and Ardnamurchan Swarms (Ch.2:II). It is not proposed to review this work once again, although a brief mention may be made here of Harker's compilation of data on the trends of dykes in Skye to reveal, as he said, "a certain tendency for the dykes to radiate from the central mountain district". A reproduction of his map (Harker,1904,p.301) is given as fig.8. It is not entirely clear on what criteria the map is based, and in this respect it is similar to diagrams presented by many other workers. Nevertheless, such maps as these are not only food for thought for, but also serve as guiders to, the author. They signify that statements of fact are credible only when backed by sufficient evidence and the details of the requisite data.

6:II. Some Difficulties Encountered during Field-Mapping.

Accuracy of measurement of the trend of a dyke is a major problem. Many outcrops have little horizontal extent. Many dykes have a sinuous strike. In the former case, little can be done to remedy the situation. In the latter case, an

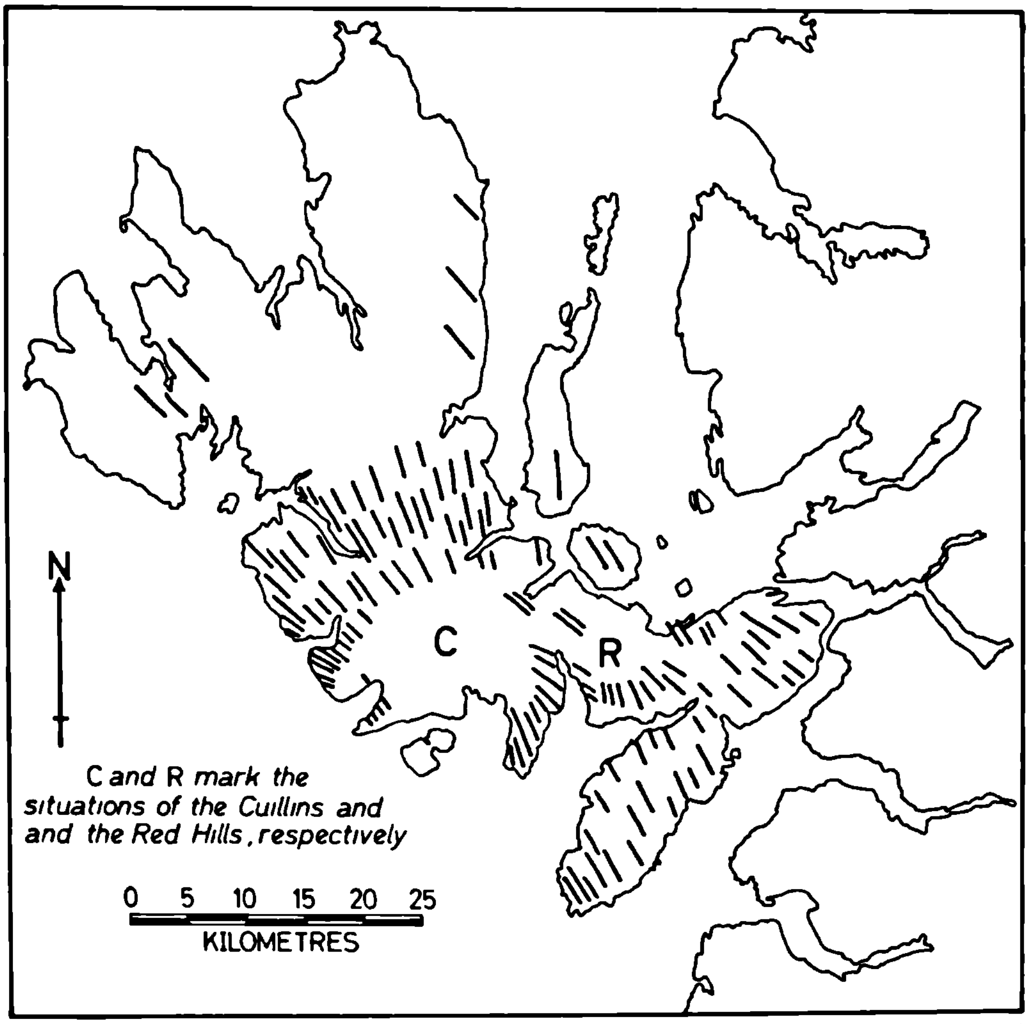


Fig 8. Trends of Basic dykes in Skye. (Taken from The Tertiary Igneous Rocks of Skye, A. Harker, Mem Geol Surv U K, 1904)

average value of the trend can be estimated, provided that the length of exposure along the strike, over several curves in the dyke's course, permits this.

Distinction between dykes of Tertiary age and older dykes is a difficulty encountered especially on the mainland southwards from Mallaig to the southern shores of Loch Linnhe. Gallagher (1963) gave an indication of the proportions of petrological types in the largely Permo-Carboniferous (but also including Devonian) suite of dykes, in an area of 40ml^2., north of the head of Loch Sunart. Of the dykes he observed, there are monchiquites (6), camptonites (35), camptonitic dolerites (13), olivine-dolerites (approximately 120). He quoted an average trend of N.70 deg.W., and an average thickness of 4ft. (1.2m.). The correspondence between both the petrology and trend of many of these dykes and those of the Tertiary swarm presents a problem of recognition, which has previously been met with elsewhere in the Tertiary Volcanic Districts (e.g. Bailey, Thomas & Anderson, 1925,pp.81-3).

A list of the field-characters used to distinguish the dykes of Permo-Carboniferous and Tertiary ages is given below. Fig.9 illustrates these characters.

CHARACTERS OF PERMO-CARBONIFEROUS DYKES	CHARACTERS OF TERTIARY DYKES
(1.) *They have a tendency to split and branch irregularly (fig. 9a).*	(1.) *They split and branch in a regular manner (fig. 9b).*
(2.) *On a large-scale their margins are sinuous (fig. 9a).*	(2.) *On a large-scale their margins are regular and straight, or smoothly-curving (fig. 9b).*
(3.) *They have variable thickness; tapering is common, with or without side-step (fig. 9a).*	(3.) *They have regular thickness; any tapering is usually accompanied by side-step to a dyke of equal thickness (figs. 9 b & d).*
(4.) *They have a very sinuous strike, one margin not always reflecting the deviations of the other (pinch-and-swell effect); any side-stepped equivalent is of irregular trend (fig. 9c).*	(4.) *They have a regular strike, or regular alternations of strike; they have regular side-step (fig. 9d).*
(5.) *They have an irregular joint-pattern; brecciation and crushing are common (fig. 9c).*	(5.) *They have a regular, rectilinear joint-pattern (fig. 9d & Plate 1).*
(6.) *They have indistinct, blotchy margins, and chilled edges are not pronounced (fig. 9e).*	(6.) *They have distinct margins, and chilled edges are pronounced (fig. 9f).*
(7.) *They are deeply-weathered, occasionally with mottled surfaces (fig. 9e).*	(7.) *Only the coarser varieties weather deeply; a smooth weathered surface is normal.*
(8.) *They are often very dark in fresh specimen.*	(8.) *They are characteristically medium-grey in fresh specimen.*

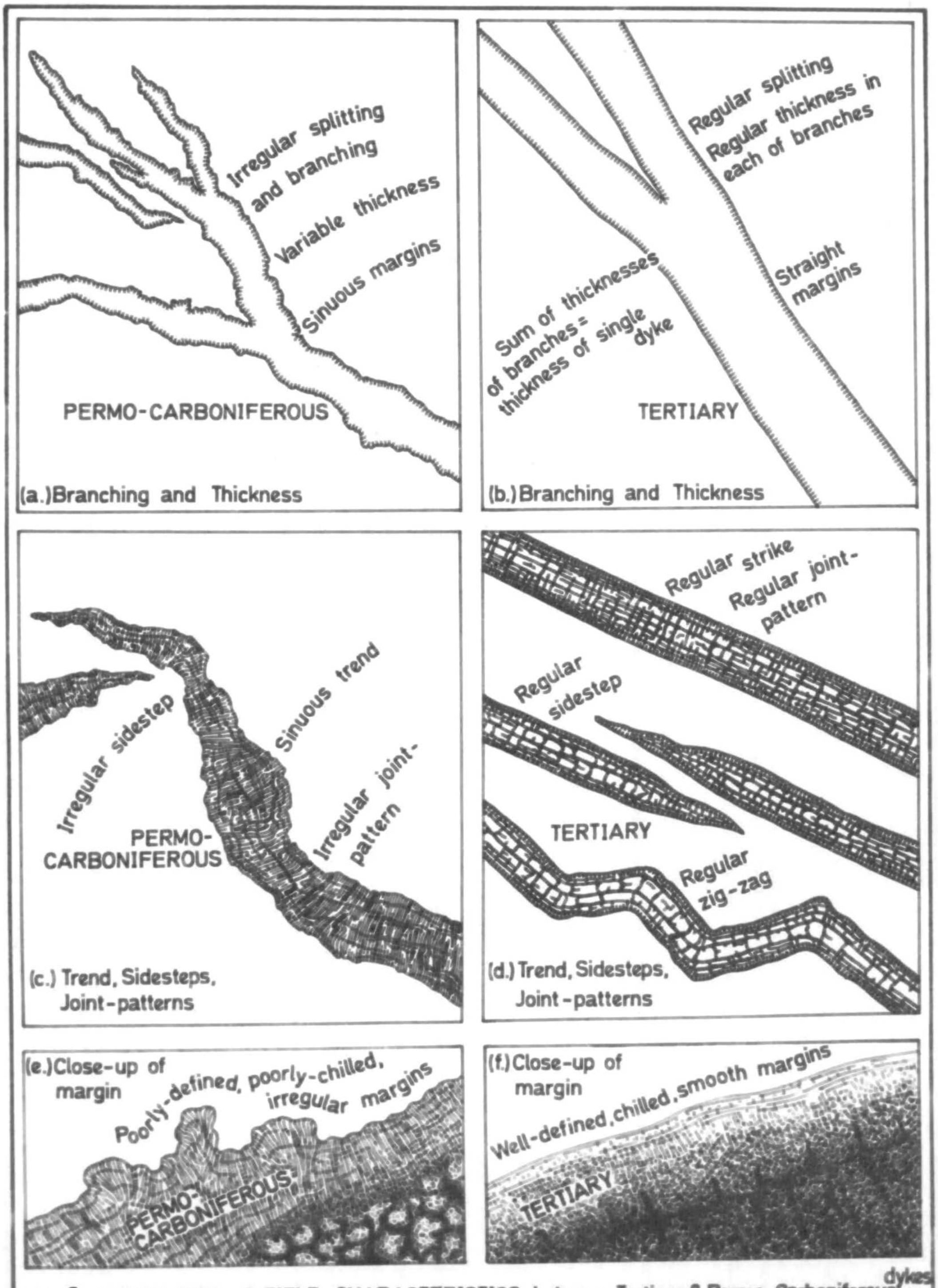
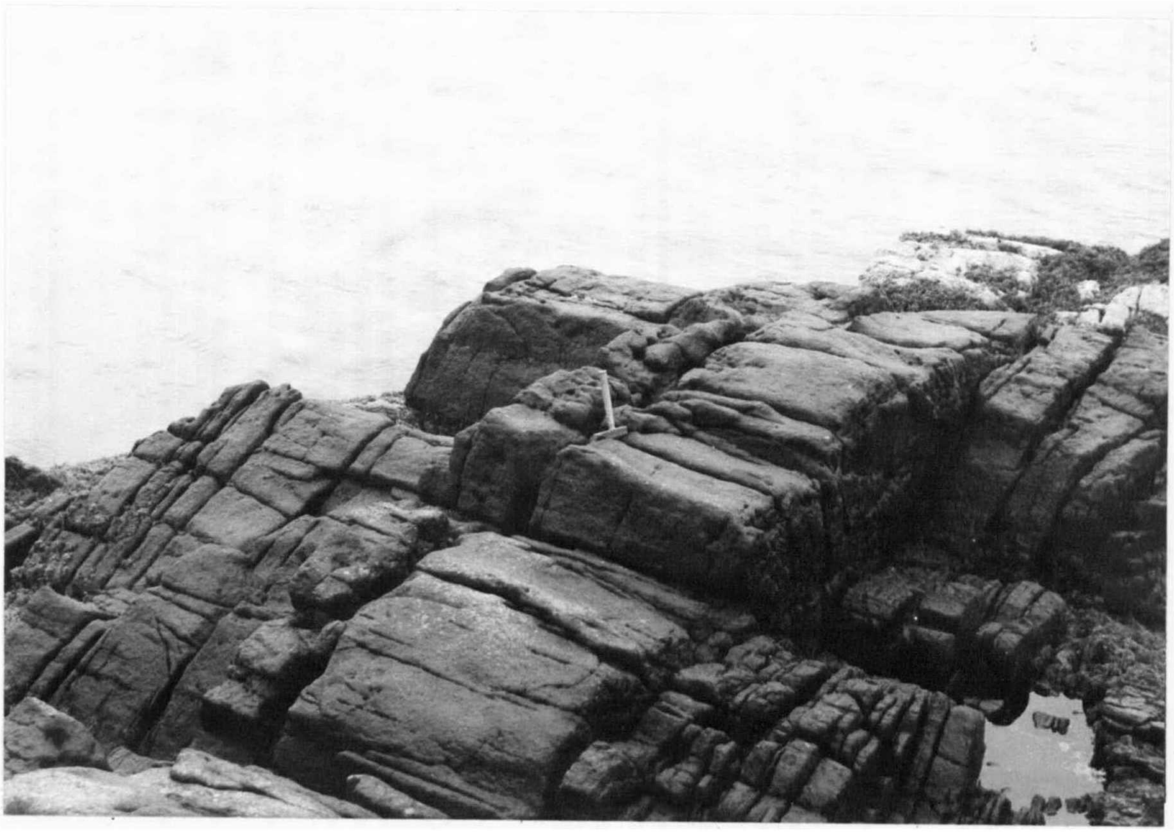


Fig. 9. COMPARISON of FIELD-CHARACTERISTICS between Tertiary & Permo-Carboniferous dykes

PLATE 1



View looking south-eastwards along a coarsely feldsparphyric, N.W., Tertiary dolerite dyke (12m. thick), at the high-water mark 1km. south-west of Tormore (south coast of Sleat). Erosion has taken place with greater facility along the cooling-joints, emphasizing to the observer their longitudinal and transverse character. (Hammer approximately 0.3m. in length. S.W. margin of dyke is just within the right-hand boundary of the photograph.)

Peach (1909,p.90), Flett (in Crampton & Carruthers,1914, p.115) and Bailey (1924,pp.377-8) each drew attention to the pustular or nodular weathering of camptonites depicted in fig.9e.

Recordings of the properties of the Permo-Carboniferous dykes, made during observation of the Tertiary dykes, point to the existence of a linear-swarm extending from Ardnamurchan to Benderloch (Appendix 26).

6:III. Problems Associated with Separation of Subswarms.

It is fitting that a description of methods used to distinguish older dykes from those of Tertiary age should be followed by one concerned with the separation of contemporaneous swarms.

The dykes of Skye and the adjacent islands (Raasay, Soay, Scalpay, Pabay) have a variety of trends which box the compass. However, except in localities to the north-east and south-west of the Central Intrusive Complex of Skye (i.e. in the Broadford Bay-Pabay-Scalpay-Applecross and the Loch Brittle-Soay districts), by far the larger proportion of trends range from 280 deg., through north, to 20 deg. of compass. The dykes in this 100-deg. interval are considered to be members of the regional linear-swarm. Such a large spread of trend seems improbable for a so-called linear-swarm. Nevertheless, the trends of the dykes in any one small area are grouped fairly symmetrically about a mean of N.W. or N.N.W., despite the great variation of trends over the whole of Skye and its adjacent islands. Furthermore, the overall numerical proportions of recordings in the upper and lower 20 deg. of this 100-deg. interval are very low.

Dykes of trend in the remaining 80-deg. interval (20 to 90 deg. and 270 to 280 deg. of compass), for the most part, outcrop at localities close to the Central Complex of Skye. In these districts, subswarms of dykes, possessing the same general trend, can be recognized. Depending upon the local circumstances, trends outside of the 80-deg. interval may also be included in these subswarms. For instance, if the dykes of the linear-swarm, in a particular area, cover a narrow, say 300 to 340 deg., spread of trend, and if all other dykes in the same area range from 10 to 70 deg. of compass, then those dykes in the 10 to 20 deg. interval (normally classed with the linear-swarm) are obviously members of some subswarm.

In regions far away from the Central Intrusive Complexes, of either Skye or Ardnamurchan, dykes of extraordinary trend (i.e. outside the common 100-deg. interval) are occasionally found again. This is especially true of the mainland from Knoydart to Loch Linnhe. In such regions there is no obvious relation to a Central Complex, and it appears that these extraordinary trends are merely due to local factors. In these cases, the dykes of these rare trends are included as members of the linear-swarm.

There is thus some degree of overlap in the separation of assemblages of trends. Common-sense and discretion are used, with allowances made for the geographical and geological location of a dyke of any particular trend. The separation has many implications. Only data on those dykes, assigned by this distinction on the basis of trend and location to the linear-swarm, is used in the analyses by the 74 groups of properties such as thickness, dip, etc., as well as trend. Only the data on these same dykes is used in the calculation of the dilation, number of dykes per kilometre, etc., for the linear-swarm.

6:IV. Separation of Subswarms.

Fig.10 is a map illustrating the geology of part of Skye and the Applecross-Loch Torridon region. In this area dykes of trend, extraordinary to the common range about N.N.W., outcrop at Scalpay, Pabay, Broadford Bay, Rubha Suisnish, the Crowlin Islands, Applecross, Loch Torridon, etc. The arithmetic-average trends of small numbers of dykes, which outcrop within short distances of one another, are indicated (also Appendix 1).

North-easterly trending dykes are found in northern and southern Scalpay, and on the southern shores at the mouth of Loch Sligachan; dykes of more northerly trend are found on the coastal section of Skye near the Narrows of Raasay. These dykes are classified as constituent members of the Scalpay-

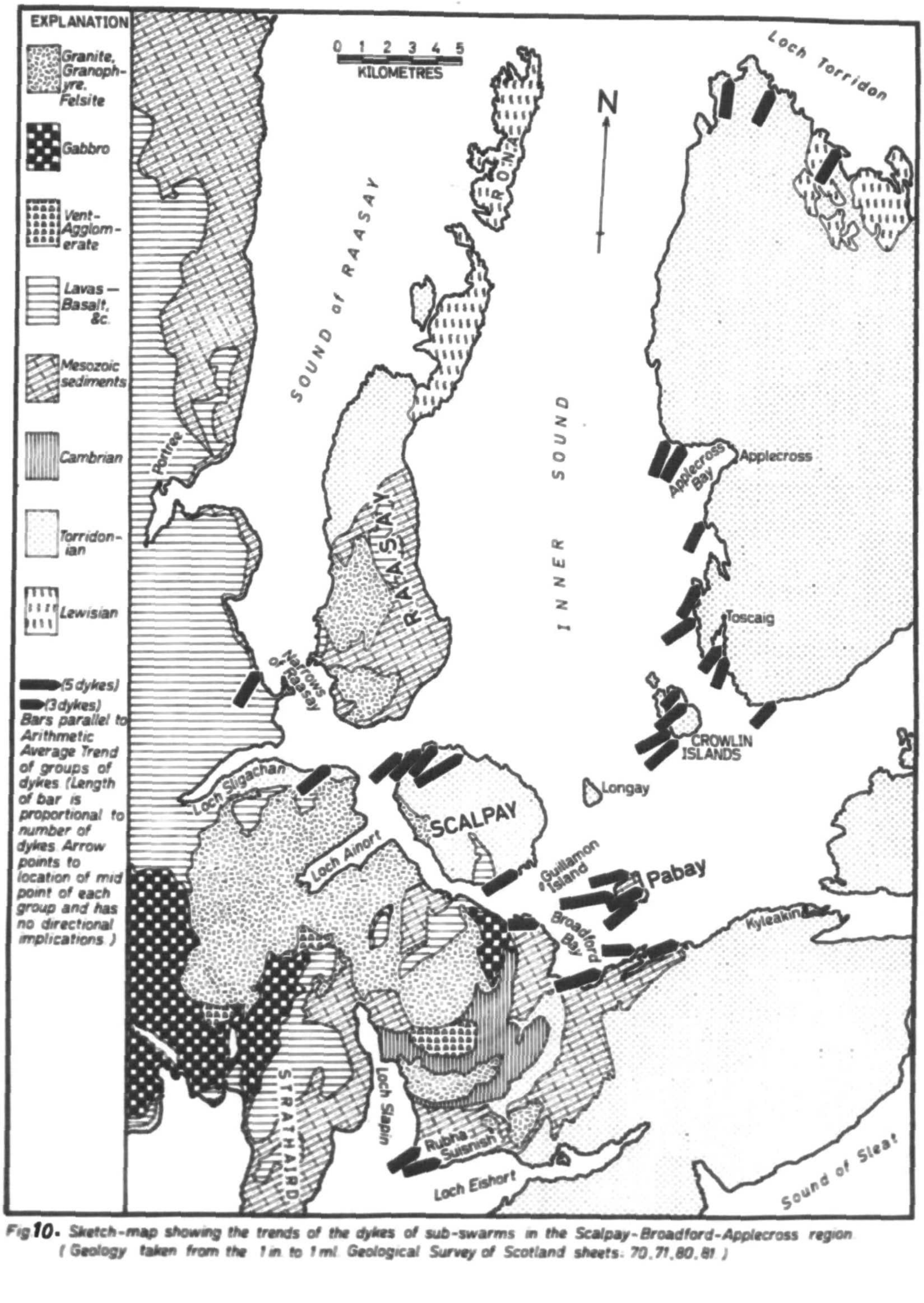


Fig 10. Sketch-map showing the trends of the dykes of sub-swarms in the Scalpay-Broadford-Applecross region. (Geology taken from the 1 in. to 1 ml. Geological Survey of Scotland sheets: 70, 71, 80, 81.)

Subswarm of north-easterly trending dykes. Dykes found at Rubha Suisnish, in coastal sections in and close to Broadford Bay, and in Pabay, have E.N.E. trends; dykes in the Crowlin Islands have N.E. trends; dykes observed from Toscaig, through Applecross, to the southern shores of Loch Torridon, have trends which veer towards N. or N.N.E. This group of dykes is classified as the Broadford Bay-Applecross Subswarm. This swarm is one with variably trending members, exhibiting a fairly regular swing between Rubha Suisnish and Loch Torridon from E.N.E. to N. to S. trends.

Dykes of N.N.W. trend in the Applecross region are extremely rare. The reasons for the inclusion of N. to S. dykes at Loch Torridon in a subswarm, rather than as members of the linear-swarm, are (i.) the regular change of trend described above, and (ii.) their distinctive distribution (Ch.7 & 8). Dykes of N.N.W. trend are, on the other hand, quite common throughout the remainder of the area occupied by the subswarms. The rôle of the N.E. dykes on southern Scalpay is uncertain. There is little evidence to indicate whether they belong to the Scalpay-Subswarm or the Broadford Bay-Applecross Subswarm (Ch.7:VI).

Fig.11 is a map of that area of Skye to the south and west of the Cuillin Hills. In the same manner as that shown on fig.10, the arithmetic-average trends of groups (in this case, of ten) dykes are represented by bars (Appendix 2).

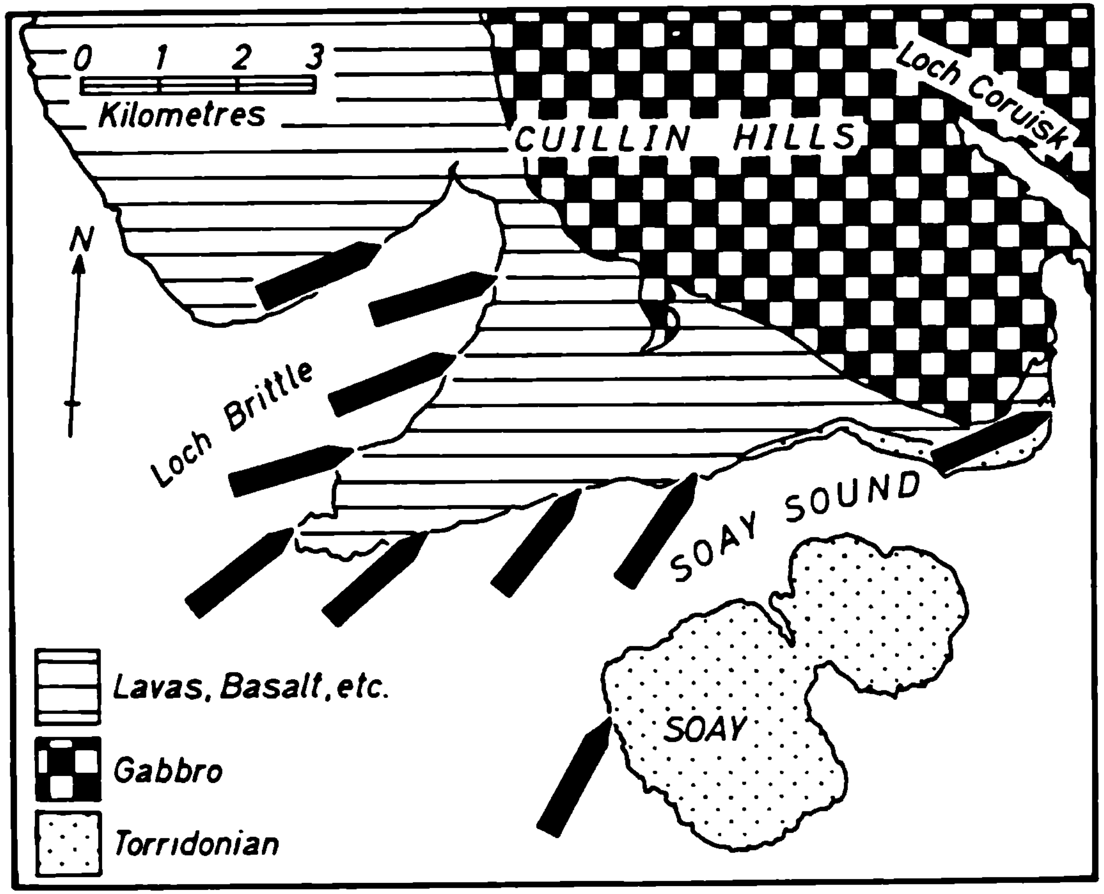


Fig 11. Map showing the trends of the dykes in the Glenbrittle sub-swarm. (Geology taken from the 1 in. to 1 ml. Geological Survey of Scotland, sheet: 70.)

(The arrow-head of the bar is of the same significance as explained on fig.10.) Again dykes of N.W. and N.N.W. trends are abundant in this area, and the N.E.-trending dykes lie well outside the range of trend of the dykes of the linear-swarm. Most of these N.E.-trending dykes are classified as members of the Glenbrittle-Subswarm of north-easterly trending dykes. There is evidence that some of the dykes (especially in Soay) belong to an off-shoot of the Rhum-Swarm (Ch. 11:VI & VII).

The dykes outcropping in coastal sections of Loch Brittle and Soay Sound appear to have somewhat of a radial disposition, with respect to some central point within the Cuillins. In contrast, however, evidence pointing to the linearity of this subswarm is given in Chapters Seven and Eight. Indeed, corroboration for the delimitation and classification of the types of all these subswarms, described above, is found in these same two chapters.

No evidence is found of well-defined subswarms associated with the Ardnamurchan Central Intrusive Complex.

6:V. <u>The Regional Linear-Swarms of N.N.W.-trending Dykes.</u>

The major part of this research-project is concerned with an analysis of the properties of the linear-swarms of N.N.W.-trending basic dykes. Much of what is stated in later chapters refers to these swarms. The subswarms, because of the low numbers of dykes they contain and not because of a lack of importance; are mentioned but briefly.

Fig. 12 demonstrates the parallelism of the trends of the dykes. A bar indicates the arithmetic-average trend for each of the groups of 100 or 50 dykes (the middle of the bar lying at the centre-spot of the group). It must be emphasized, again, that in this and all other work dependent upon the use of the 74 groups, the data on the dykes of the subswarms has been excluded.

Fig. 12 clearly exhibits the general N.N.W. trend of the dykes. The radial disposition of dykes about the Cuillins and Red Hills is not as pronounced as Harker showed it (fig.8), and this may well be because of his failure to extract dykes of subswarms from his observations. There is, nevertheless, a certain degree of "fanning" from a more north-westerly to a more north-north-westerly trend, from west to east across the central part of Skye, north of the Cuillins. Notable, too, is the fairly smooth change from Strathaird, through Sleat, to Morar and Moidart, from a N.N.W. to a N. to S. average trend (also Appendix 3). Dykes of Ardnamurchan have a fairly constant average trend of about N.N.W. (Seventeen dykes on parts of the south-east coast of Harris have an arithmetic-average trend of 327deg. of compass: the spread of the trends is from about 290 to 350deg.)

Fig. 13 makes use of the same data on the arithmetic-

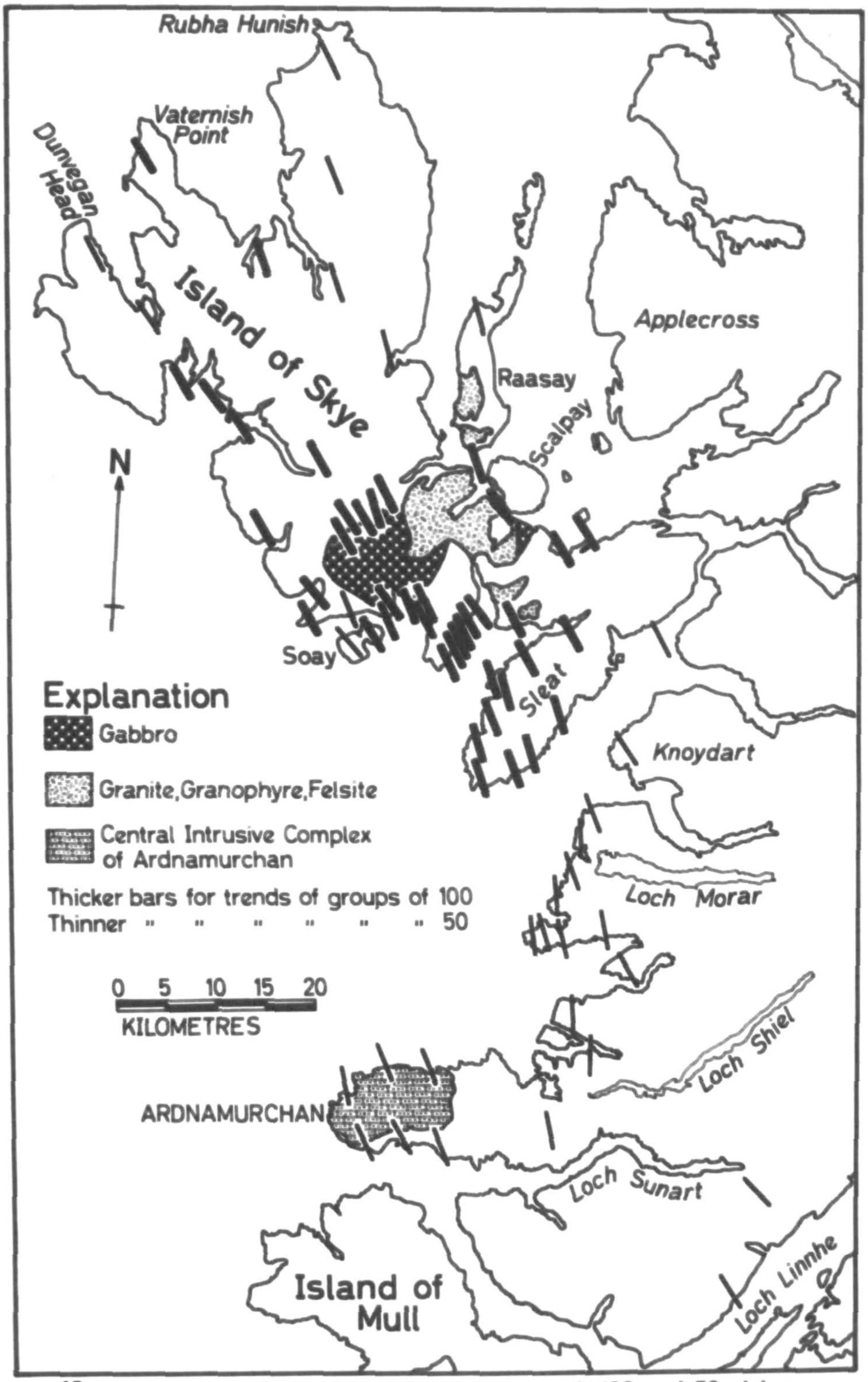


Fig. 12. Average trends (arithmetic) for groups of 100 and 50 dykes. Representation by orientated bars.

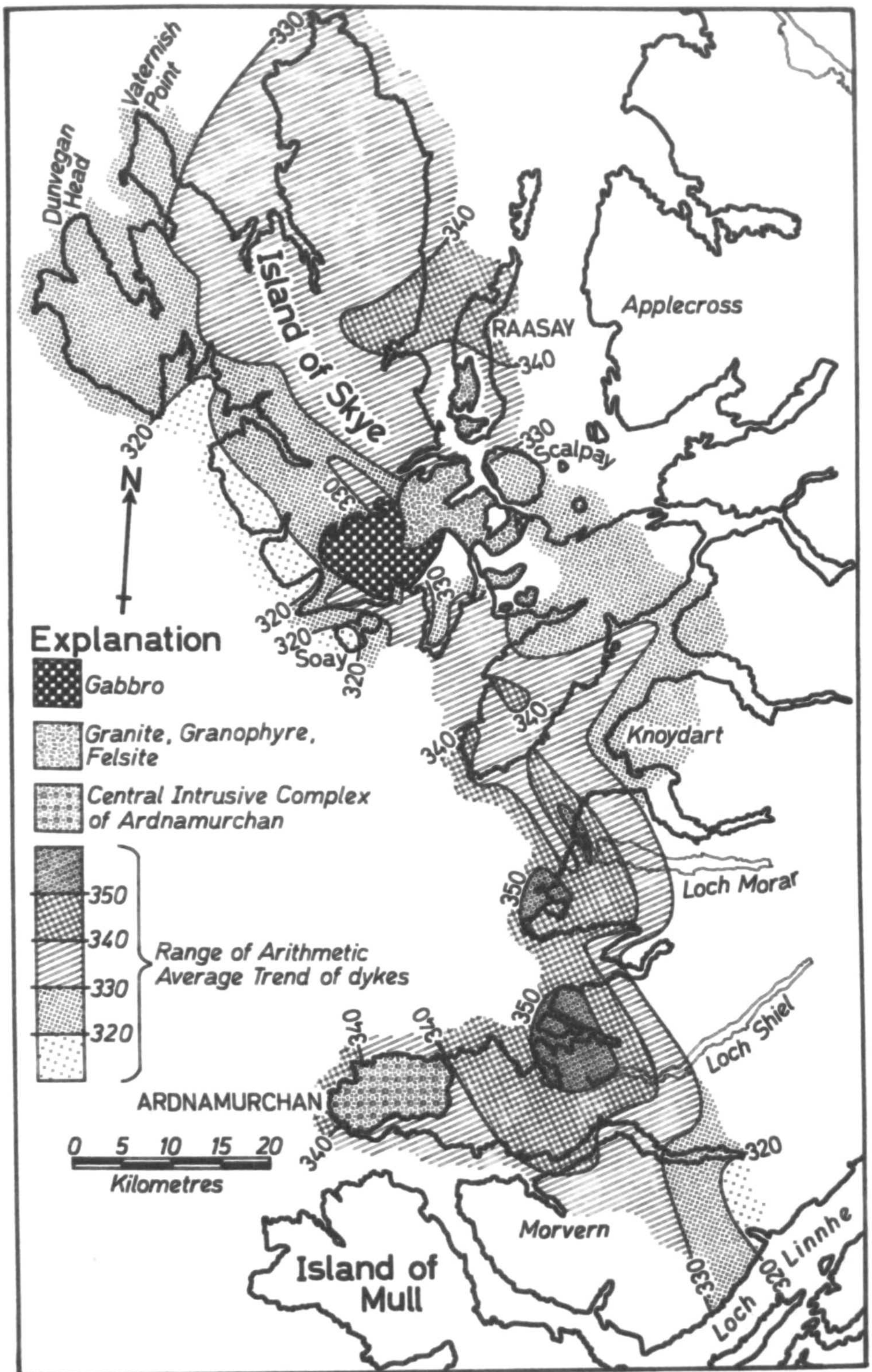


Fig. **13.** *Arithmetic-average trends for groups of 100 and 50 dykes. Representation by contours.*

average trend for the 74 groups. The average for each group is allocated to the corresponding centre-spot, and an approximate contouring is employed to illustrate the geographical distribution of 10-deg. intervals of arithmetic-average trends. In many ways this map is more elucidatory than the previous map. It especially highlights the "fanning" of trends across northern Skye, and the swing in trend from Strathaird through to Moidart. This latter, however, appears to be an irregular change, especially for averages in the 350 to 360deg. range.

An analysis on a large-scale in certain respects more clearly demonstrates the major swings in the trend of the dykes. Fig. 14 constitutes just such an analysis. Nine broad regions covering the Area of Study, except Harris, are shown on this map, each accompanied by a rose-diagram illustrating the distribution of the trends of all the observed dykes which belong to the linear-swarm. Each rose-diagram is plotted using 5-deg. intervals. The justification for such a small interval is in the large number of dykes in each region. The regions contain different numbers of dykes, but in all cases the frequency-distribution is reduced to a percentage-basis (Appendix 4).

The regions are so chosen as to indicate in the clearest manner possible some of the general changes in the trend throughout the swarm. Above all else, the rose-diag-

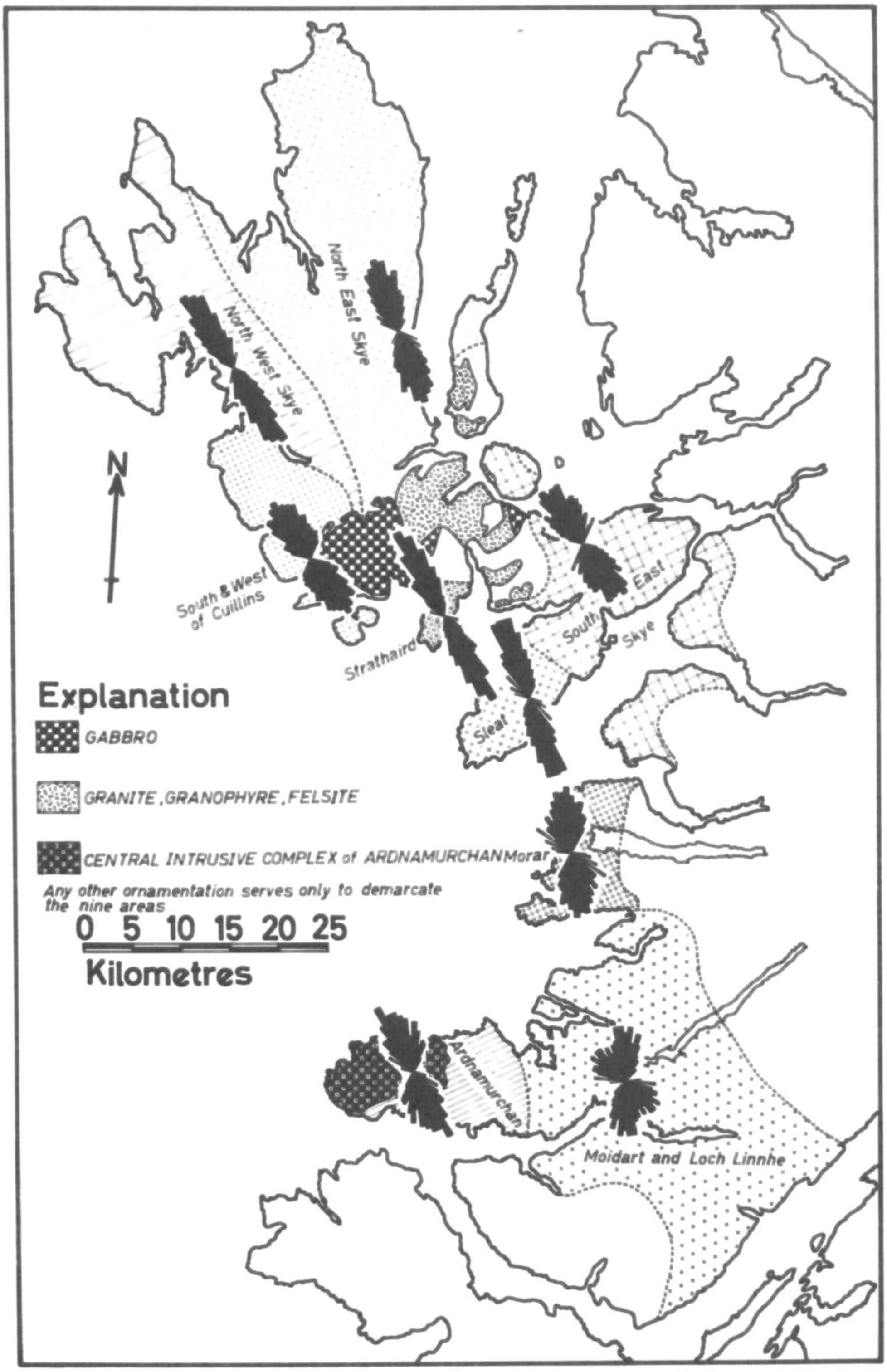


Fig. 14. Sketch-map to show the major characteristics of the variations of the trend of the dykes. Analysis of the trends is in nine groups, each of which includes dykes from a wide range of localities.

rams illustrate the frequency-distribution or variation of the trend of the dykes, and this serves as a useful preliminary analysis in this type of study.

The narrow spread of trend in the north-west and north-east of Skye, and in Strathaird and Sleat, are easily perceived. This change from a N.N.W. geometric-mean to a more northerly average in passing from north-western to north-eastern Skye, and the similar swing from Strathaird to Sleat, are both immediately obvious. Large spreads of trend to the south and west of the Cuillins, and in south-eastern Skye are depicted. The larger spread in Morar, in the Moidart and Loch Linnhe district, as well as the swing from Sleat through to these two regions towards inclusion of more dykes of northerly trend, are also portrayed. Ardnamurchan has a trend-distribution of more north-westerly character than the adjoining Moidart region. The spread of the trend near the Ardnamurchan Central Complex is more pronounced than, for instance in Strathaird, near the Skye Central Complex.

A discussion of the construction of the rose-diagrams is a necessary adjunct to the description of fig.14. Circular-nets of equal-area, rather than equal-interval, are used for two reasons: (i.) low values in any one interval of trend become lost to the eye of the observer when plotted on equal-interval nets, and large values appear disproportionately large, and (ii.) plots on an equal-area net of trend-distribution, on a percentage-basis, whether of narrow or broad spread, all rightly appear to involve a total of 100 units, whereas this would not be the case using equal-intervals. There is further justification in that rose -diagrams express more graphically what a histogram portrays: histograms are equal-area plots and rose-diagrams must be the same to be truly representative.

The frequency-distribution of the trend of the dykes for the whole of the Skye-Swarm is shown in fig.15. The definition of the "Skye-Swarm" is difficult to explain at this stage, since it largely depends on evidence given in Chapter Seven. Here it may be said briefly that distinction from the Ardnamurchan-Swarm is on the basis of the existence of a "corridor" of low-intensity of dykes between the two swarms. Distinction from the Mull-Swarm is on a similar though not so reliable basis.

The Skye-Swarm includes, in the case of fig.15, data on the dykes of the various subswarms described above, and the total number of observations is above six-thousand (6159). This total bears but an approximate relationship to the actual total number of dykes in the swarm. As already stated, the latter number appears to be incalculable.

Inclusion of data on dykes of the subswarms serves to illustrate crudely the insignificance of their numbers rela-

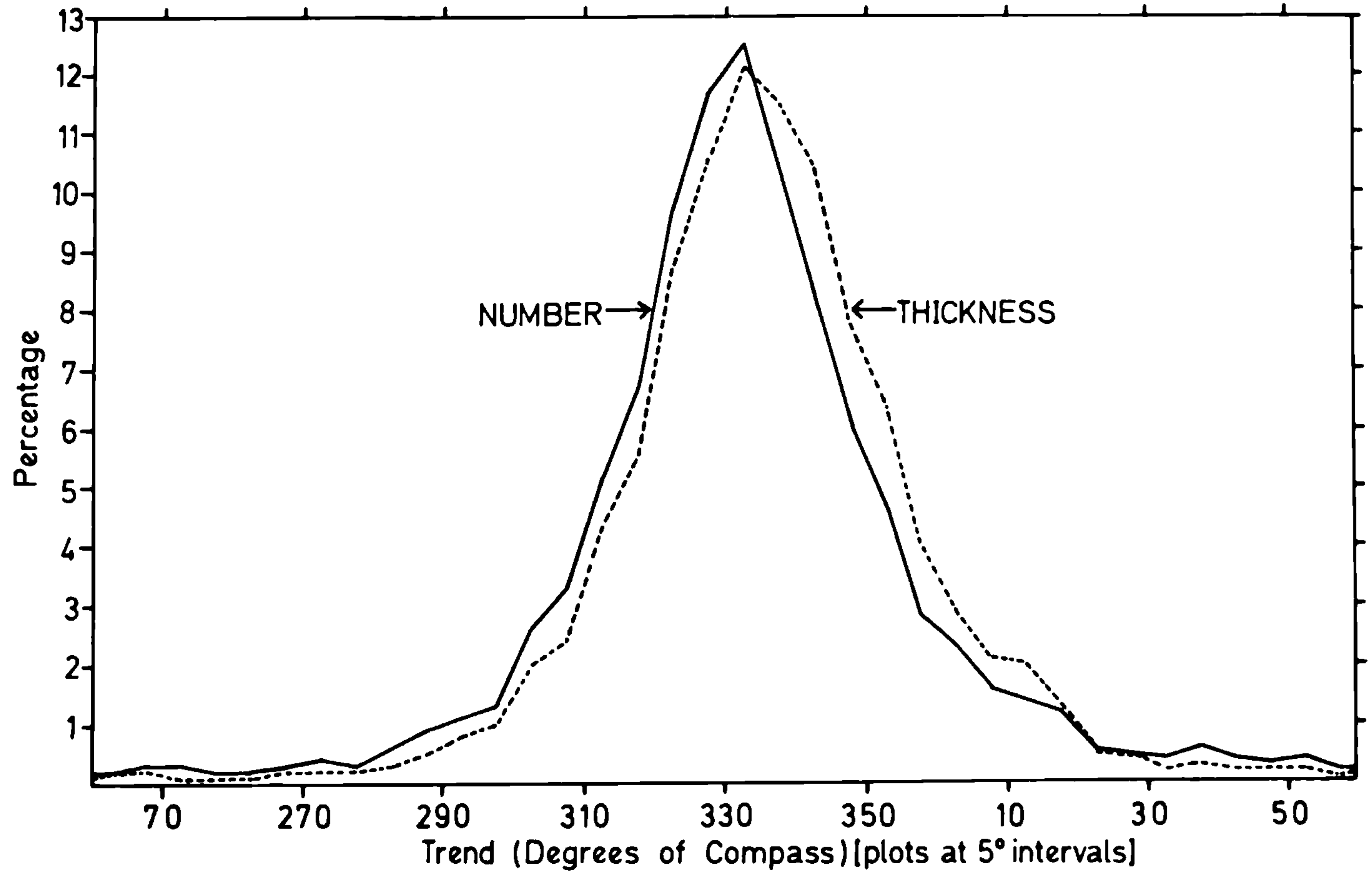


Fig. 15. FREQUENCY-DISTRIBUTION of TREND by NUMBER and SUMMATED THICKNESS
SKYE SWARM. Total: 6159 dykes.

tive to those of the regional linear-swarm of N.N.W. dykes. Taken out of context in this manner, the N.E. dykes, etc., appear to be an integral part of an almost perfect Gaussian -Distribution, with a peak at about 330deg. of compass (fig. 15). However, remarks made earlier in this chapter, as well as in later chapters, indicate their distinctiveness. (When the possible mechanisms of origin of the Hebridean dyke-swarms are considered in Chapter Sixteen, it is on the other hand found that the views expressed here must be slightly modified.) In later chapters, too, a more precise account of the relative intensity of numbers of dykes in the sub-swarms, in comparison to those of the regional linear-swarm, is given.

Dykes have the property of breadth: the problem arises as to whether a frequency-distribution graph of trend should be constructed on a basis of the number of dykes, or on a basis of the summated thicknesses of dykes within intervals of trend. Both are plotted on fig.15 (data in Appendix 5), and their coincidence is remarkable. The slight displacement towards northerly trends of the "thickness-plot" is worthy of note, and an explanation of this is offered in Chapter Nine (II).

Similar graphs are presented (fig.16 : data in Appendix 4) for the nine broad regions demarcated previously in fig.14. Again a close correspondence of the two curves is

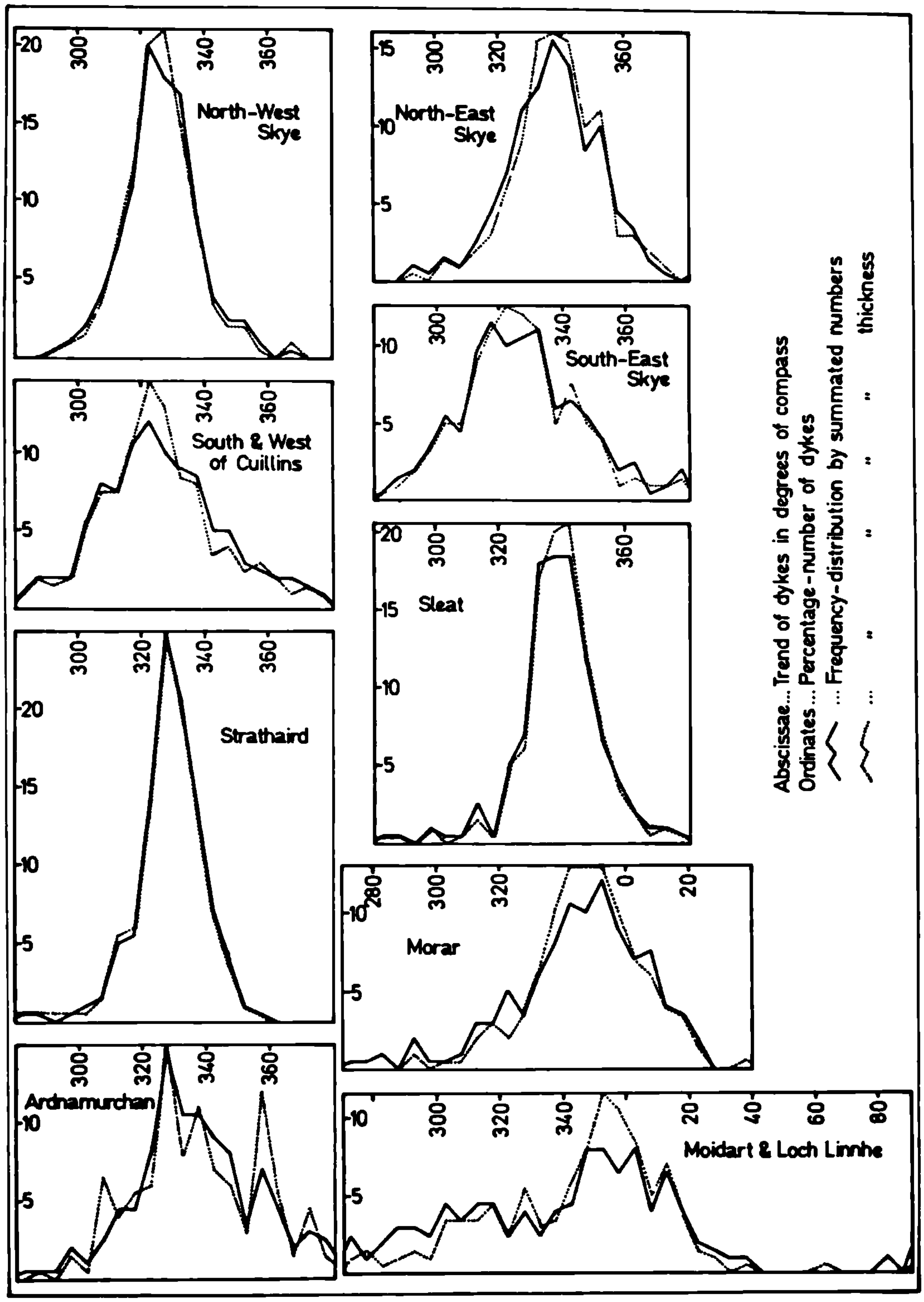


Fig.16. Trend-analysis by number and summated thickness for nine large areas

evident. However, the peak of the "thickness-plot" is often at a higher percentage than the peak of the "number-plot". This points to a tendency for dykes of median trend in certain areas to be of a broader nature, and vice versa.

As mentioned earlier, the frequency-distribution of trends in the nine groups, each covering a broad area, serves as a preliminary analysis in work of this kind. A minutely detailed description of the variation and geographical distribution of the trends of the dykes is given in the form of Appendix 6, and the corresponding rose-diagrams of figs. 17 to 32. These are based on the 74 groups of 100 or 50 dykes. Again, each rose-diagram is plotted on an equal-area net: the outer circle is at 50 per cent.

Certain problems, concerning the selection of intervals associated with the analysis of the trends of the dykes, can be conveniently discussed at this stage. If a histogram is plotted using one-deg. intervals, a series of many peaks, which are difficult to interpret, is the result. For example, in the range 340 to 349 deg. of compass, inclusive, there may be 30 dykes: 11 at 340deg., 11 at 349deg., and the remaining 8 at one to each intervening degree. Single-degree analysis gives two pronounced peaks. However, the sum of the numbers of dykes in the ranges 340 to 344deg., and 345 to 349deg., is 15 in both cases. A 5-deg. interval plot removes the peaks.

Obviously, this process can be carried too far. Nevertheless, using groups of 100 or 50 dykes, and breaking the data down into 5-deg. intervals (340 to 344, 345 to 349, etc.), and then building-up into 10-deg. intervals (either 340 to 349, etc., or 345 to 354, etc.) is successful in obliterating relatively meaningless double-peaks. For example, a series of values in 5-deg. intervals may be :-

0,1,3,6,18,6,9,15,6,3,1,0;

and on building-up into 10-deg. intervals this becomes:-

either 1,9,24,24,9,1 ..... single-peak,

or 4,24,15,21,4 ..... double-peak.

The former seems preferable, and yet there is the ever-present problem as to whether a double-peak is significant or not. Despite this, wherever possible double-peaks are removed by the method outlined above. It may be added that in favour of the removal, where possible, of double-peaks are two facts : (i.) the frequency-distribution for the Skye-Swarm (fig.15) shows no double-peak, and (ii.) the 10-deg. interval used is possibly too small (from a purely statistical viewpoint) in many groups to confirm with absolute certainty the validity of double-peaks.

A similar problem arises in the calculation of the geometric-mean trend. This, too, is deduced by computing from 5-deg. intervals the 10-deg. interval which contains the maximum number of dykes. Consequently, the 10-deg. interval may be in the form, 345 to 354deg., or 350 to 359deg.,etc., or may even cover a 15deg. range where values in two overlapping 10-deg. intervals are the same. Ideally, a single-degree distribution should be used to calculate the 10-deg. geometric-mean, which may then have the form 343 to 352 deg., etc. However, the geometric-mean value of trend is only used in one context (fig.34, and its explanation later in this chapter), where the map derived is very approximate, and warrants no more accurate a determination than a build-up from values in 5-deg. intervals.

Criticisms levelled here, concerning the choice of intervals, can also be levelled in later chapters at the analyses of thickness and dip of dykes. Questions of statistical validity are mentioned above and have already been discussed at length in Chapter Five. To subject the choice of intervals to rigorous statistical tests for validity would doubtless reveal anomalies, and yet, as explained in Chapter Five (III), these are inevitable in a study of this nature.

To describe the rose-diagrams of figs. 17 to 32 at great length would defeat their purpose, which is to present in the most illustrative form a detailed analysis of the trend. Exhibition of the data in pictorial form is presumed to be that most comprehensible to the majority of readers. Consequently the following constitutes the very briefest of descriptions.

Figs. 17 to 20 (excluding '11' on fig.20) portray the distribution of trends within groups located mainly in the lava-pile of northern Skye. There is a narrow spread of trends within any one of these groups, and double-peaks are of minor development and rare. The average trend is near N.N.W. A closer study reveals some swing in trend through from groups shown on fig.17 to '2' and '3' (fig.18), to '5A' and '5B' (fig.20), and '0A' (fig.18). This again demonstrates the "fanning" of the trends from west to east. Group '11' (fig.20) shows a wide spread of trend with no pronounced maximum.

Fig.21, and '21' and '22' on fig.22 show groups south and west of the Cuillins. A truly gregarious assemblage of trends is characteristic of these localities. Many of the trends are N.W. to N.N.W., but peaks at W.N.W. and at N. to S. are also present. In complete contrast, groups '23', '24', '25' (fig.22), and the four groups on each of figs. 23 and 24, exhibit an extremely narrow spread of trend, with no double-peaks, and an almost Gaussian-Distribution, averaging at N.N.W.

Fig.25 has five groups in areas east of the Central Intrusive Complex. Comparison with groups in Strathaird (figs.23 & 24) illustrates how much broader and irregular is the spread of the trend in groups of fig.25. The varia-

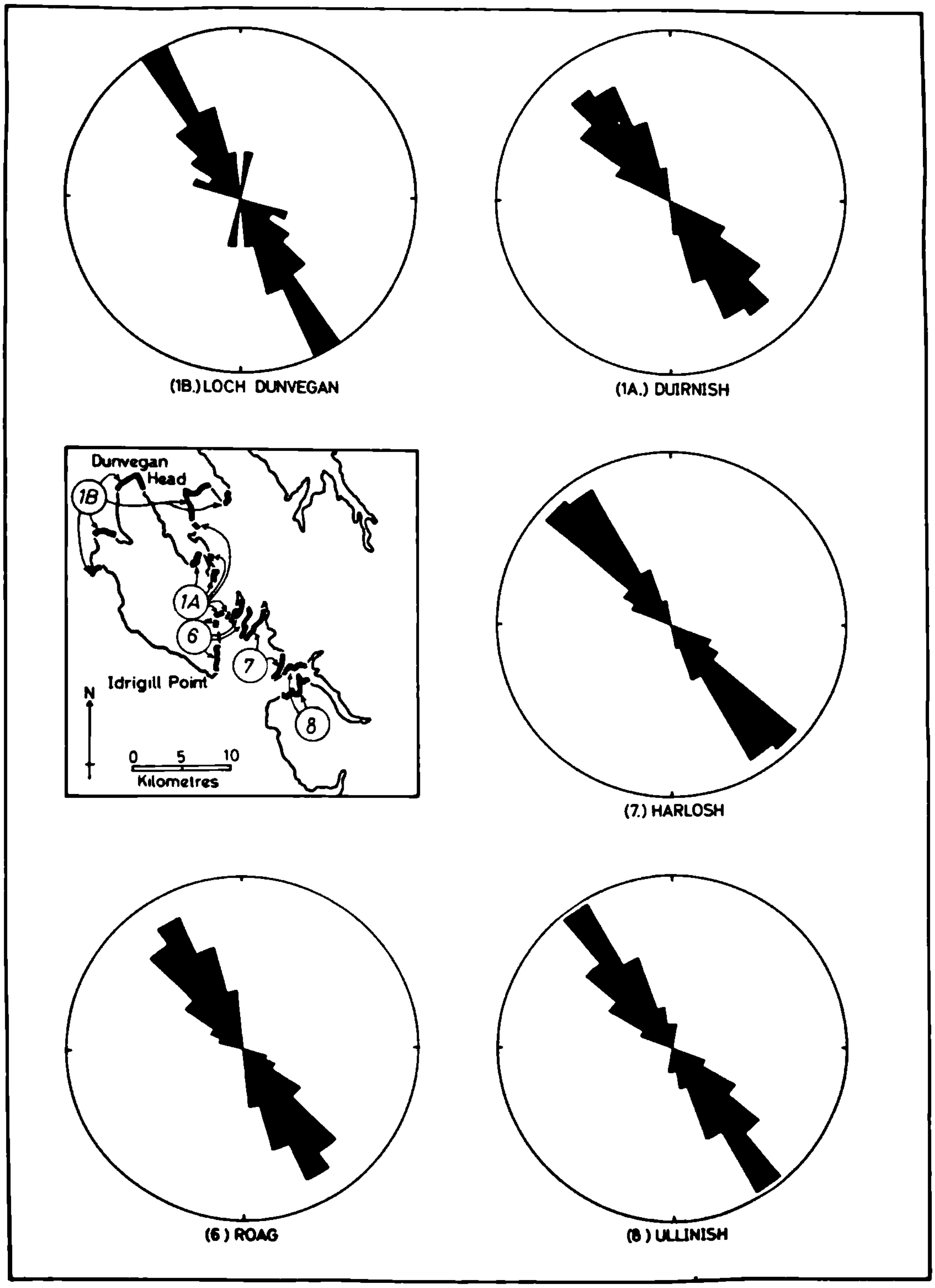


Fig.17. Trend-analysis

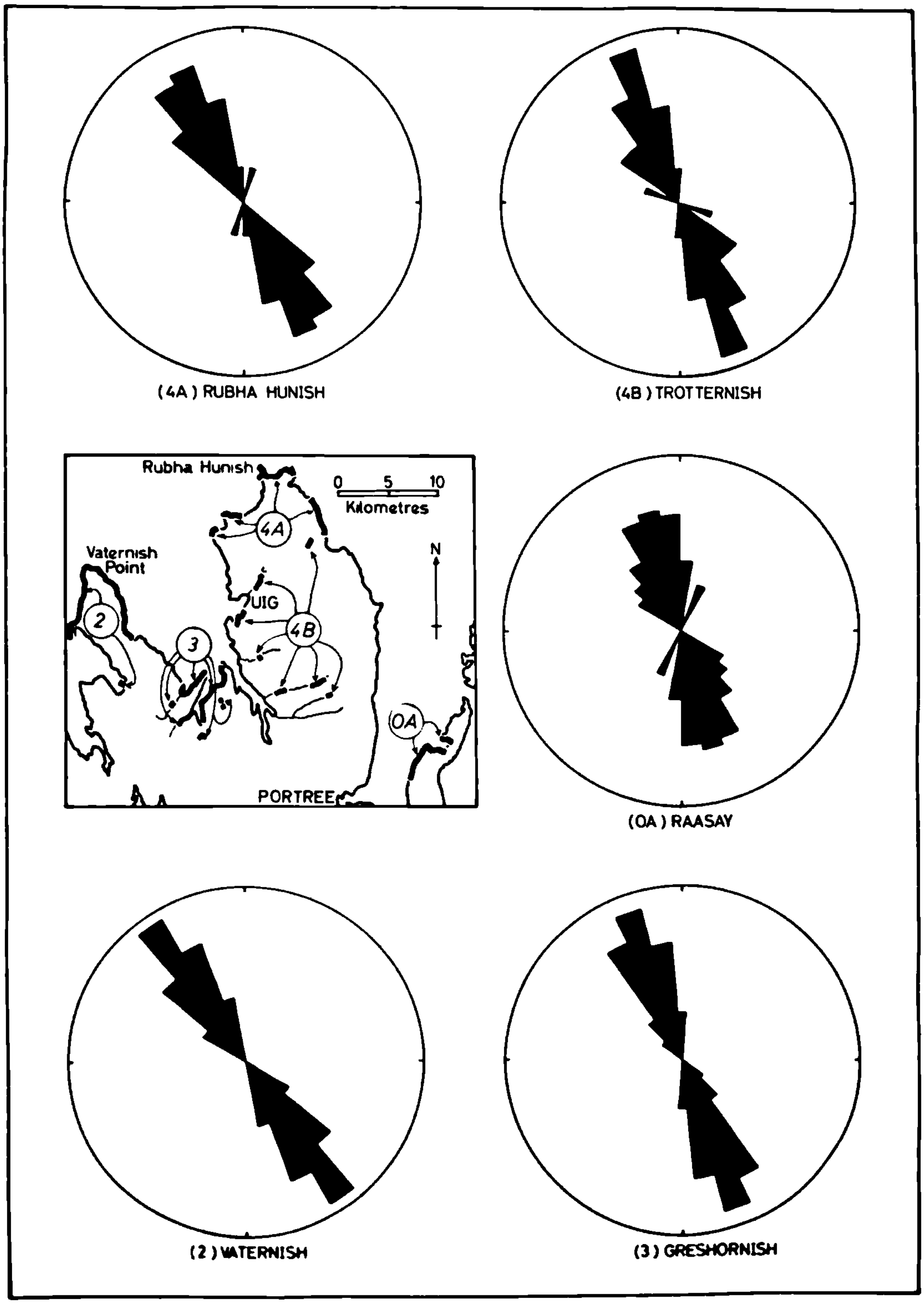


Fig.18. Trend-analysis

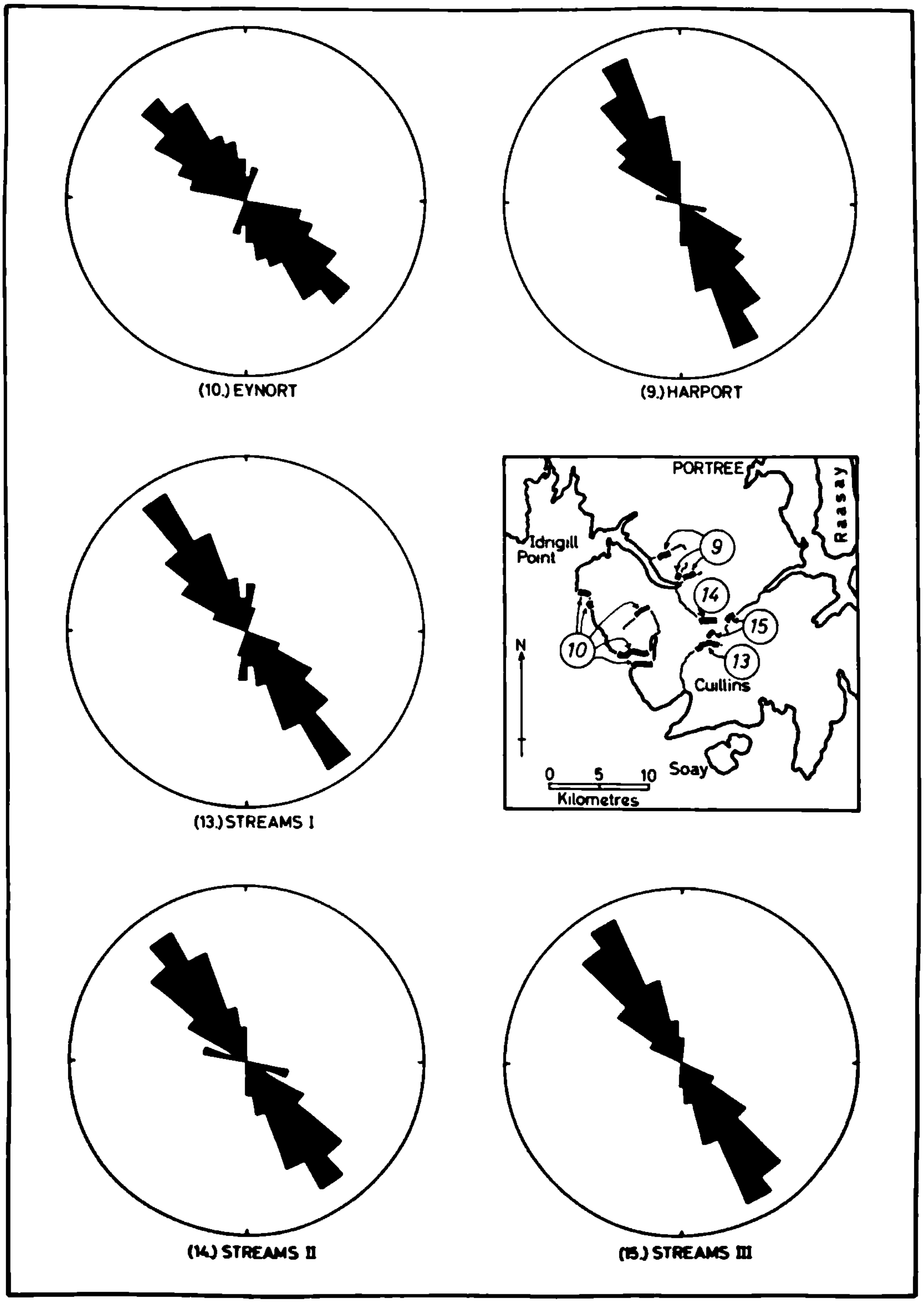


Fig.19. Trend-analysis

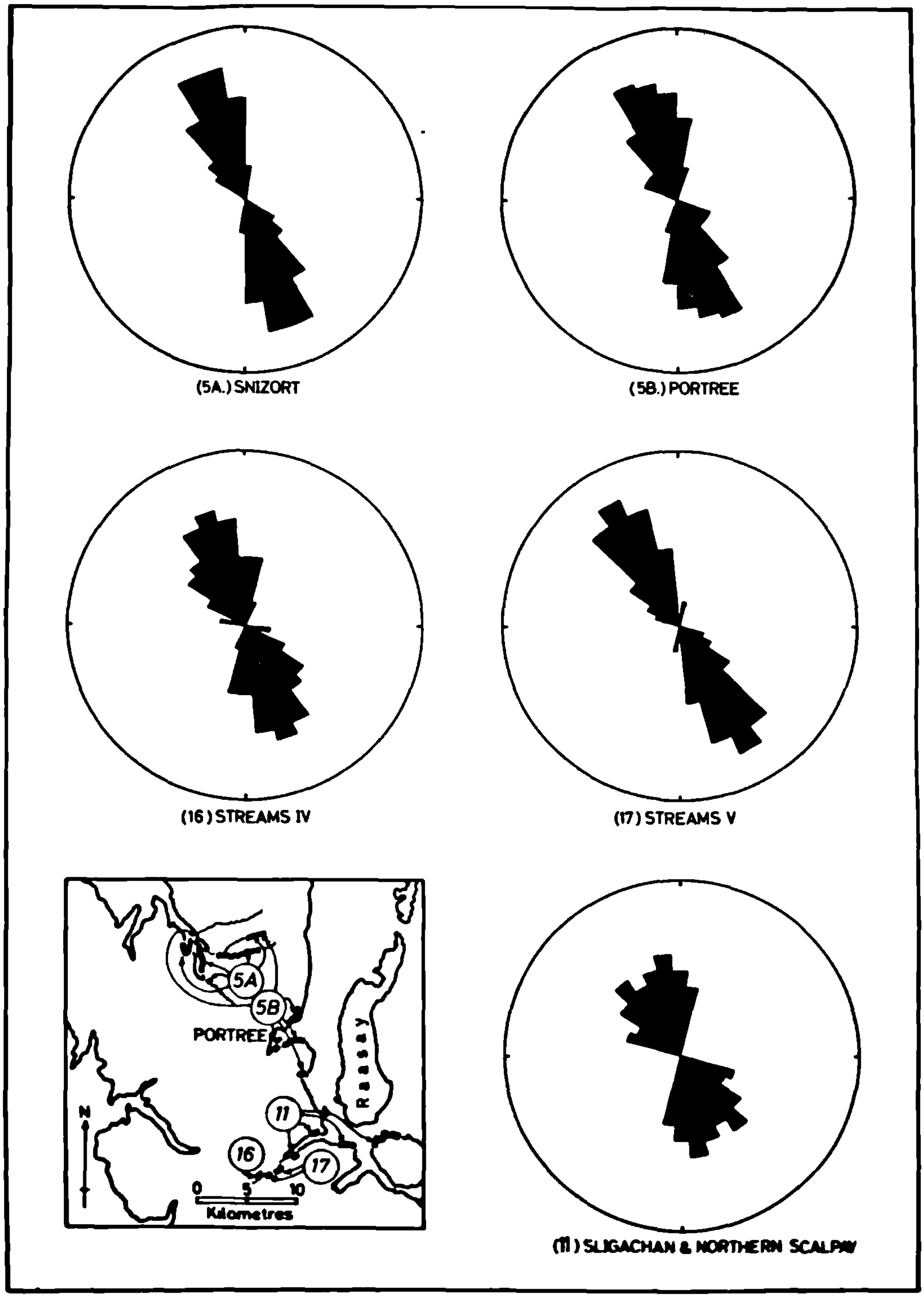


Fig.20. Trend-analysis

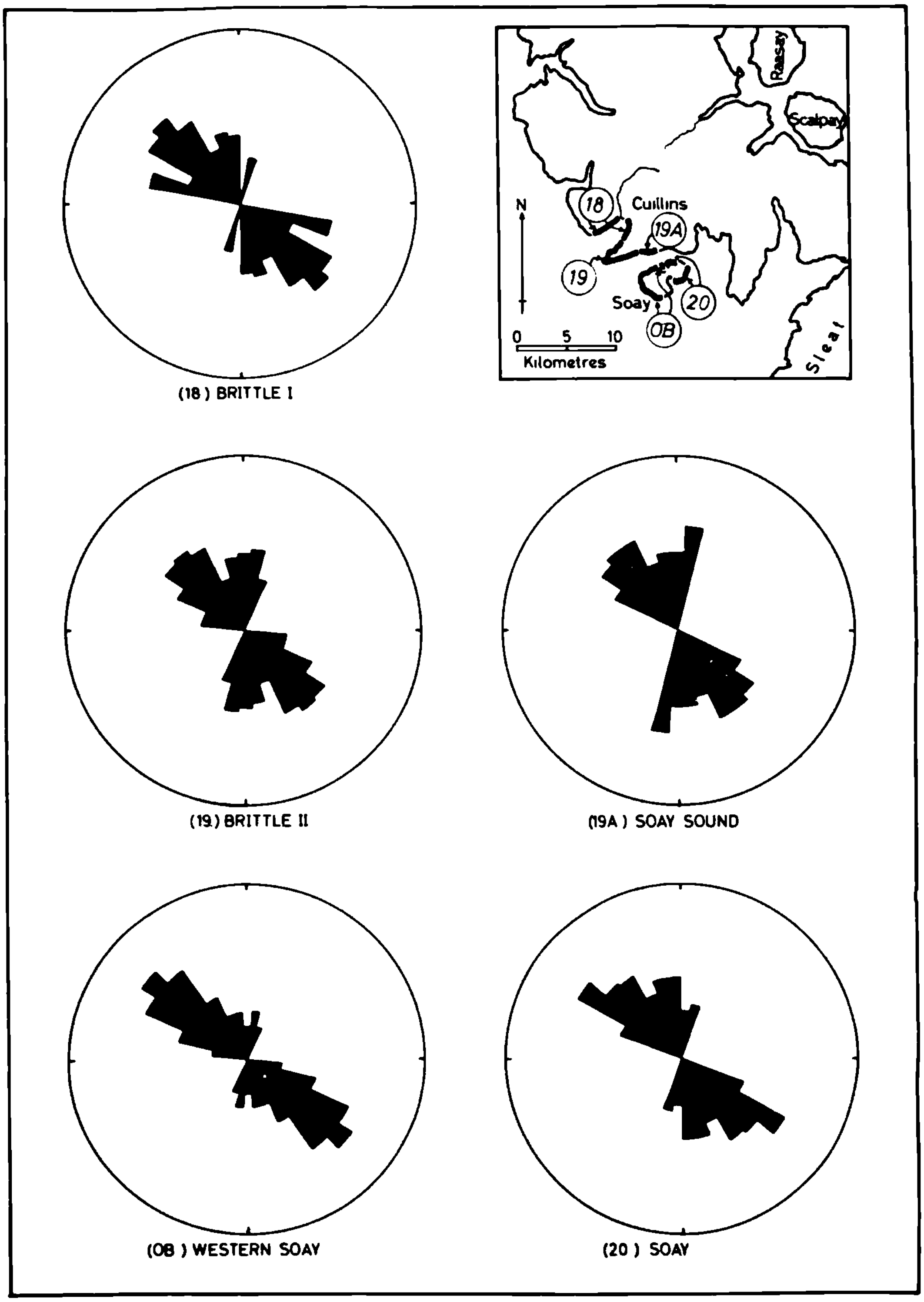


Fig. 21. Trend-analysis

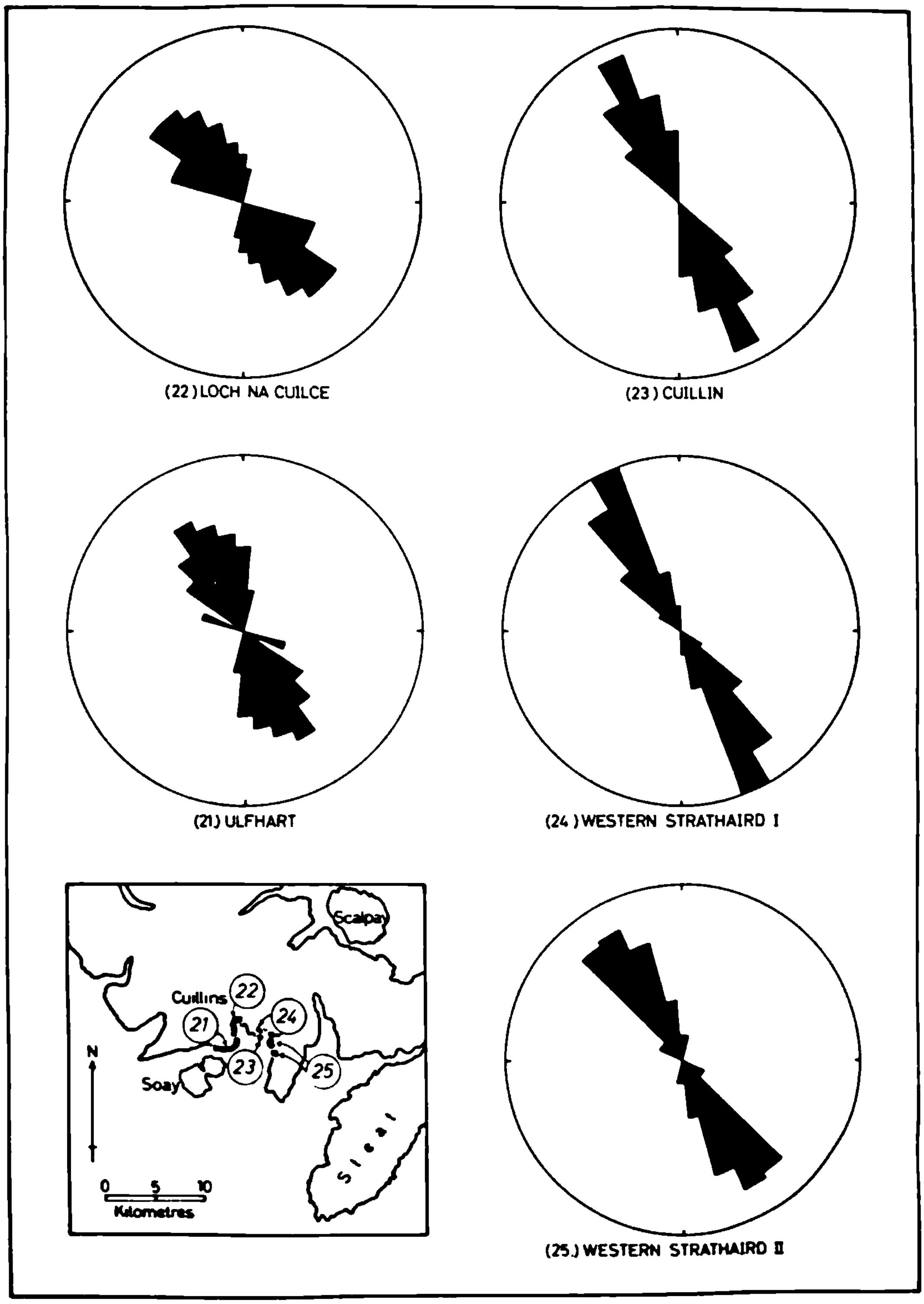


Fig. 22. Trend-analysis

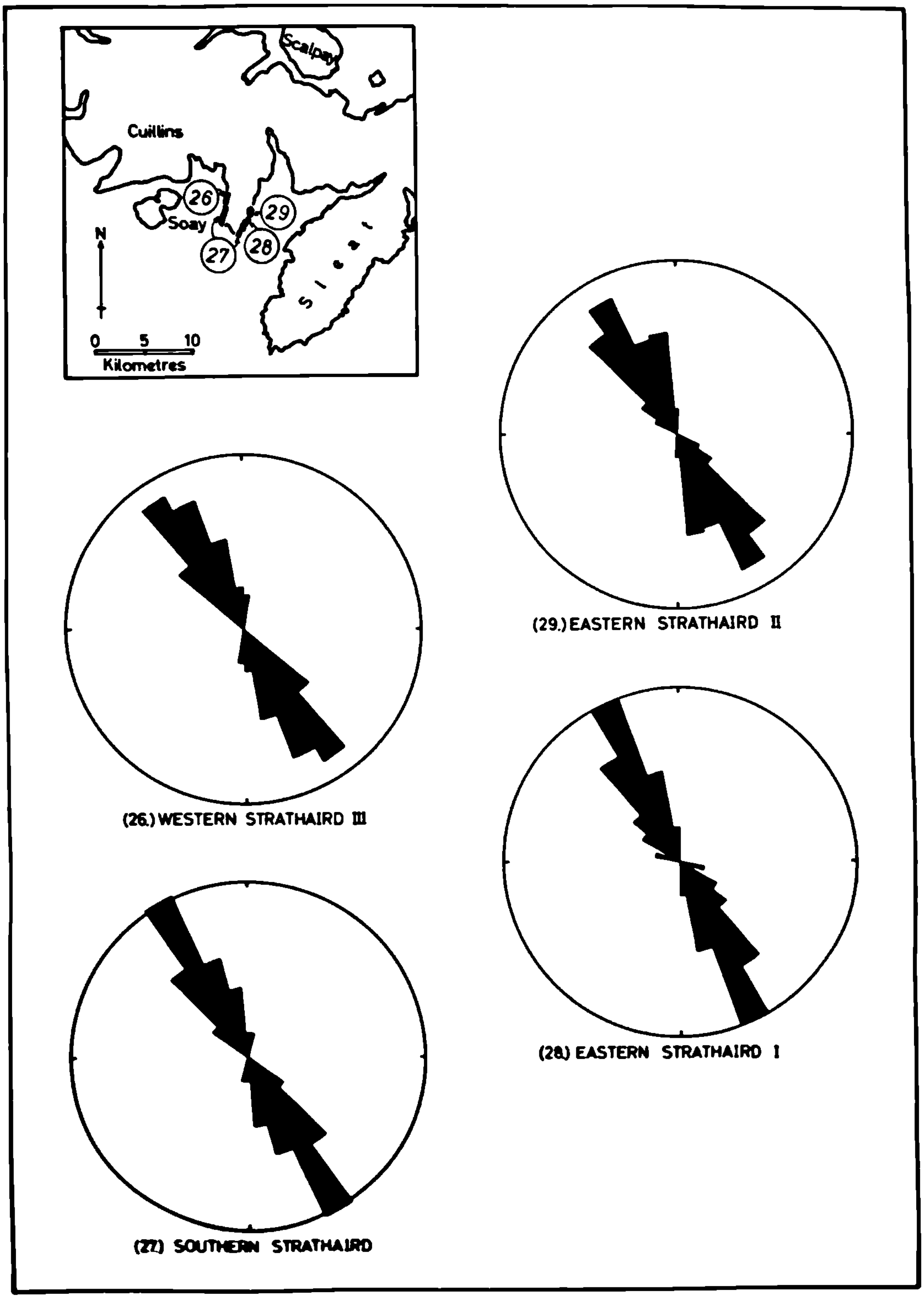


Fig.23. Trend-analysis

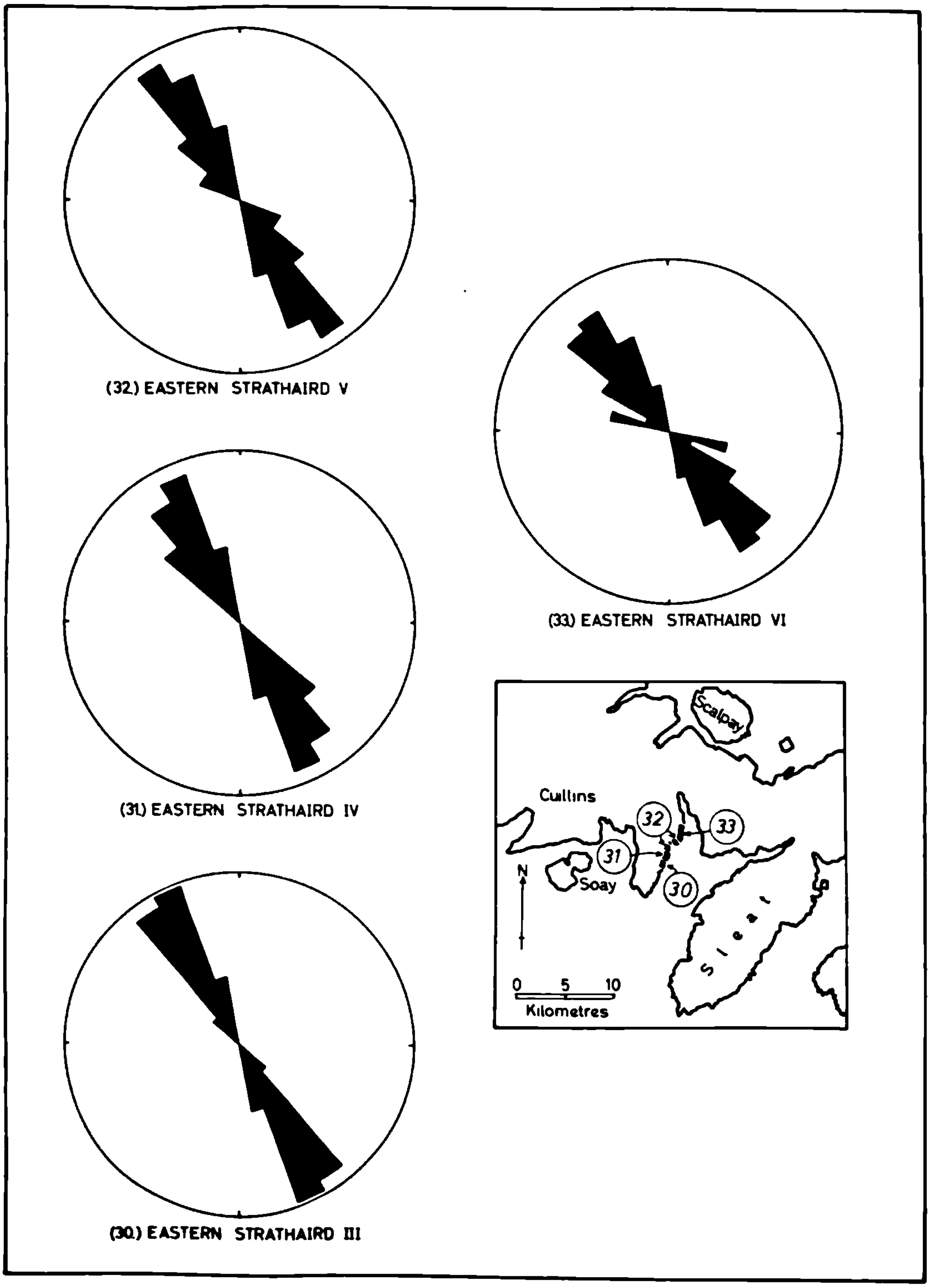


Fig.24. Trend-analysis

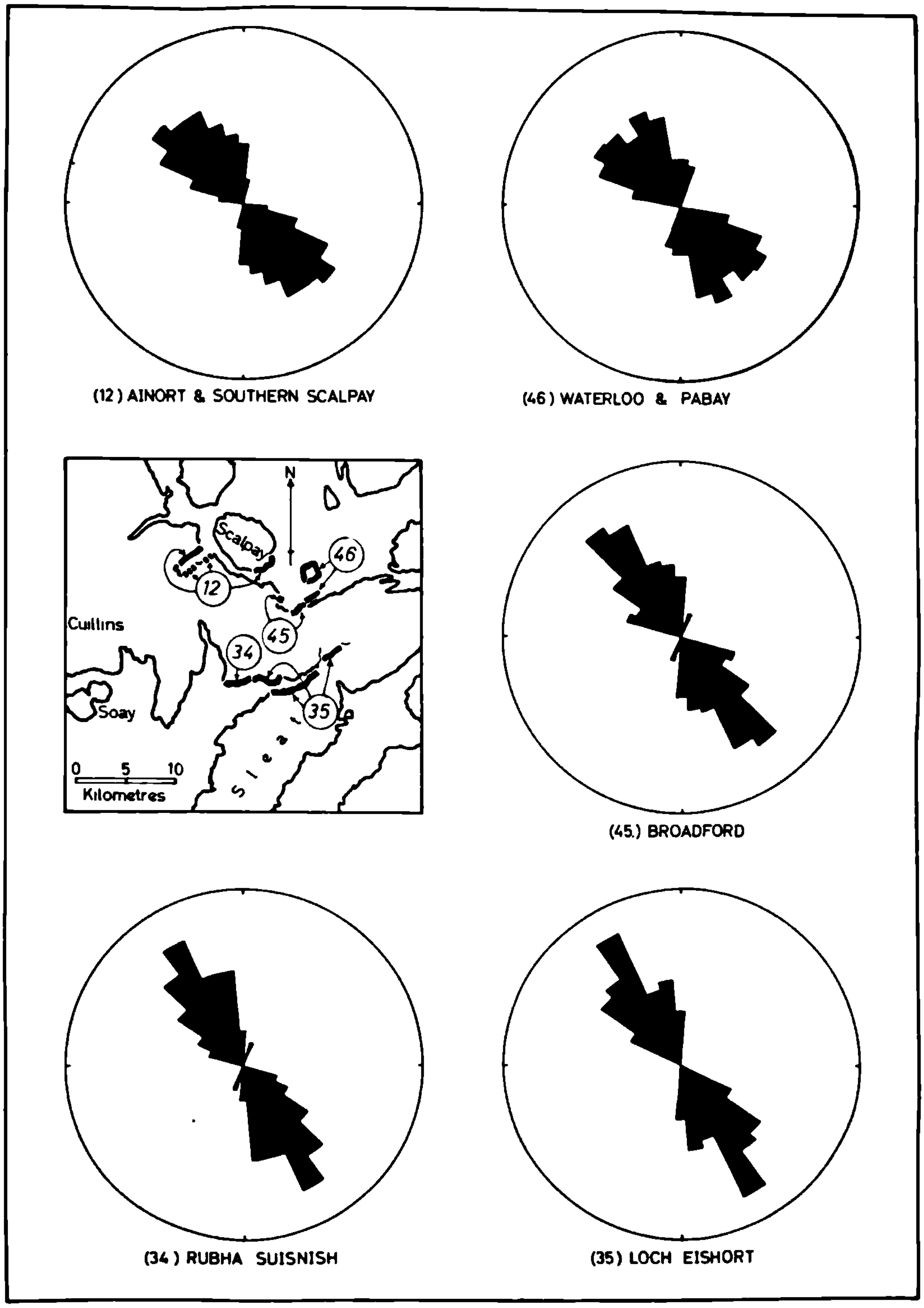


Fig.25. Trend-analysis

bility of the trend is developed not to the extremes found to the south and west of the Cuillins, for in some measure the distribution is almost Gaussian despite the variability, i.e. double-peaks are largely lacking.

Figs. 26 and 27 illustrate the trend-distribution in groups located in the south of Skye. As in Strathaird, though slightly less well-developed here, the spread of the trend is small and roughly Gaussian. The distribution becomes more irregular in groups '44' and 'OC' (fig.27). The geometric-mean trend is more northerly in groups in southern Skye than in the groups of Strathaird. In group 'OH' (fig.28) the distribution is similarly of narrow and even spread, although the trends are markedly more northerly. The remaining four groups on fig.28, the five on fig.29, and 'ON', 'OO', and 'OP' on fig.30, covering areas in Knoydart, Morar, Moidart, and Sunart, show the same dominance of northerly trending dykes. Very noticeable, irregular and broad spread of trend is apparent in most of these groups, with pronounced double-peaks in some cases. In some the double-peaks are of N. to S. and N.N.W. trends; in other cases E. to W. trends are abundant, e.g. 'OD' and 'OE' (fig.28), and 'OM' (fig.29).

In groups 'OQ' and 'OR' (fig.30) the N. to S. component is very much reduced, and the N.W. trends become prominent again, though double-peaks are fairly well displayed.

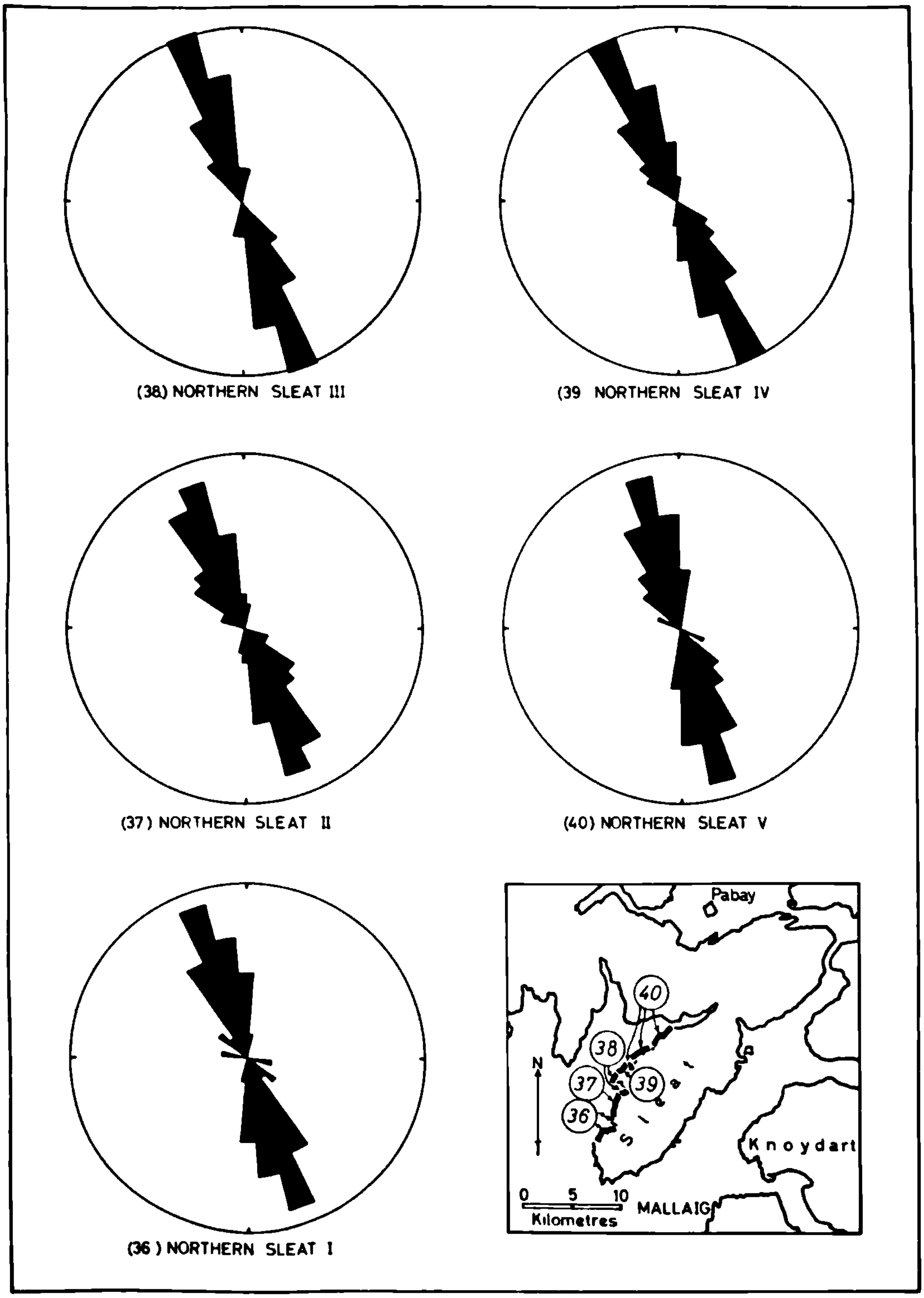


Fig.26. Trend-analysis

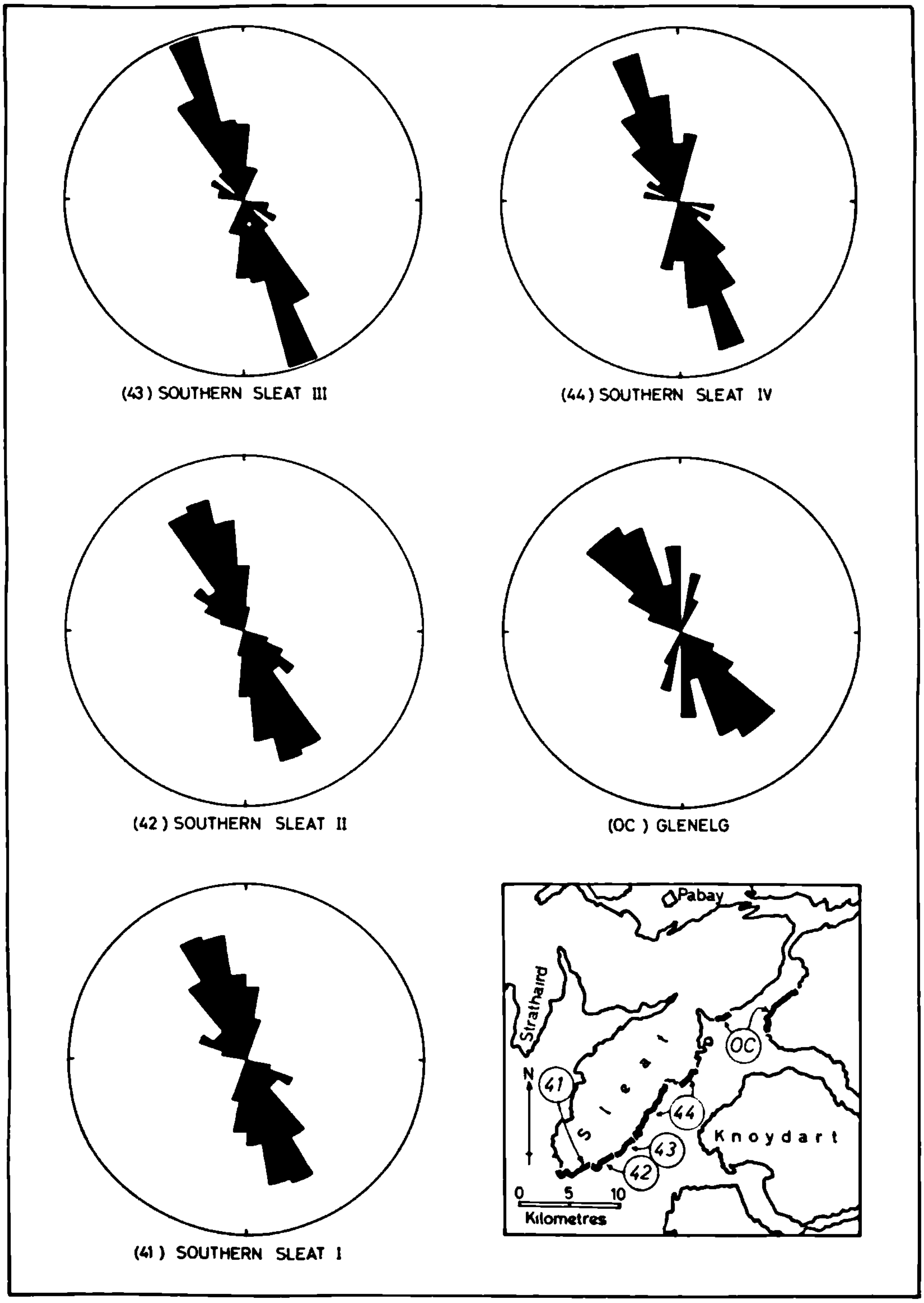


Fig.27. Trend-analysis

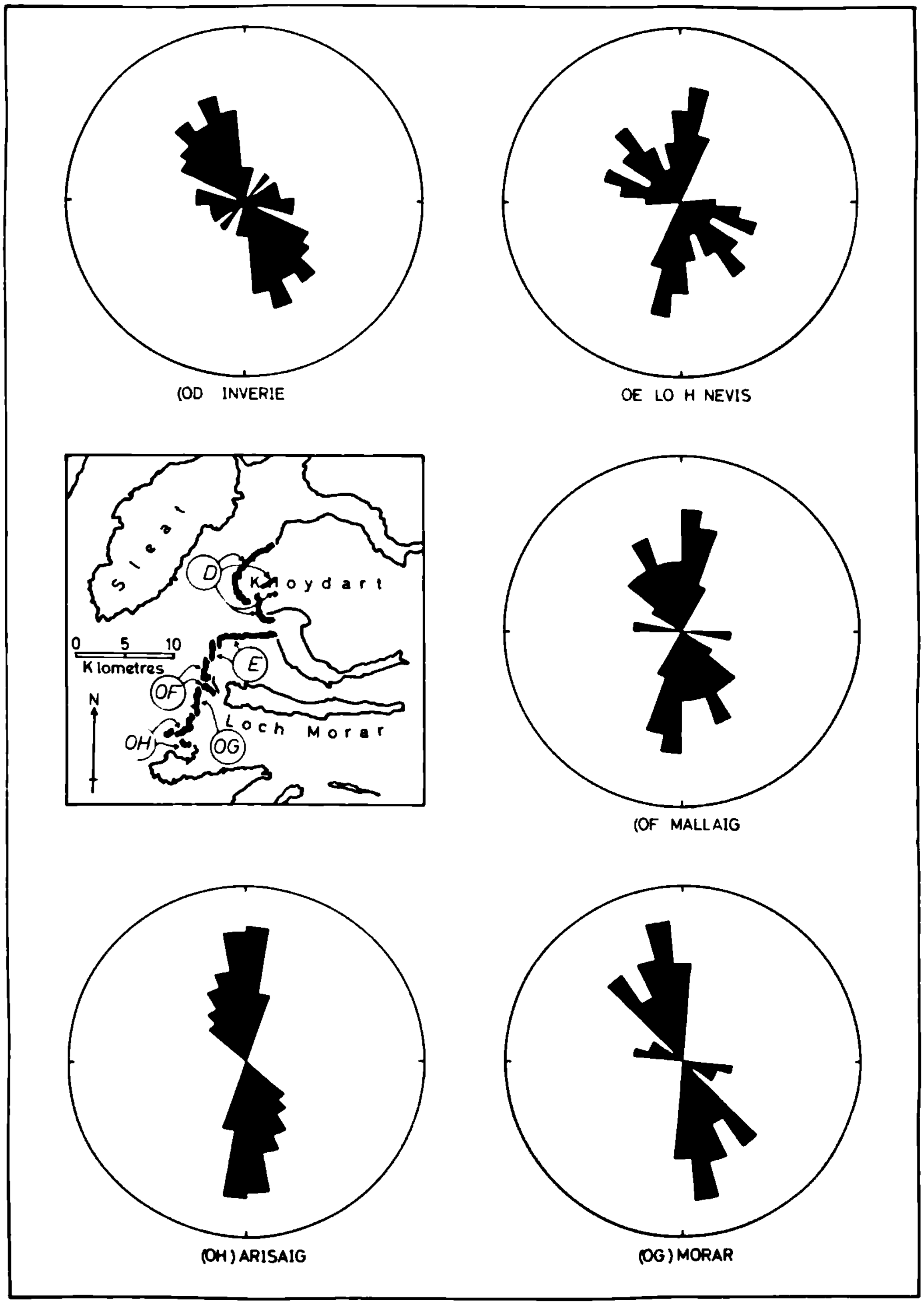


Fig.28. Trend-analysis

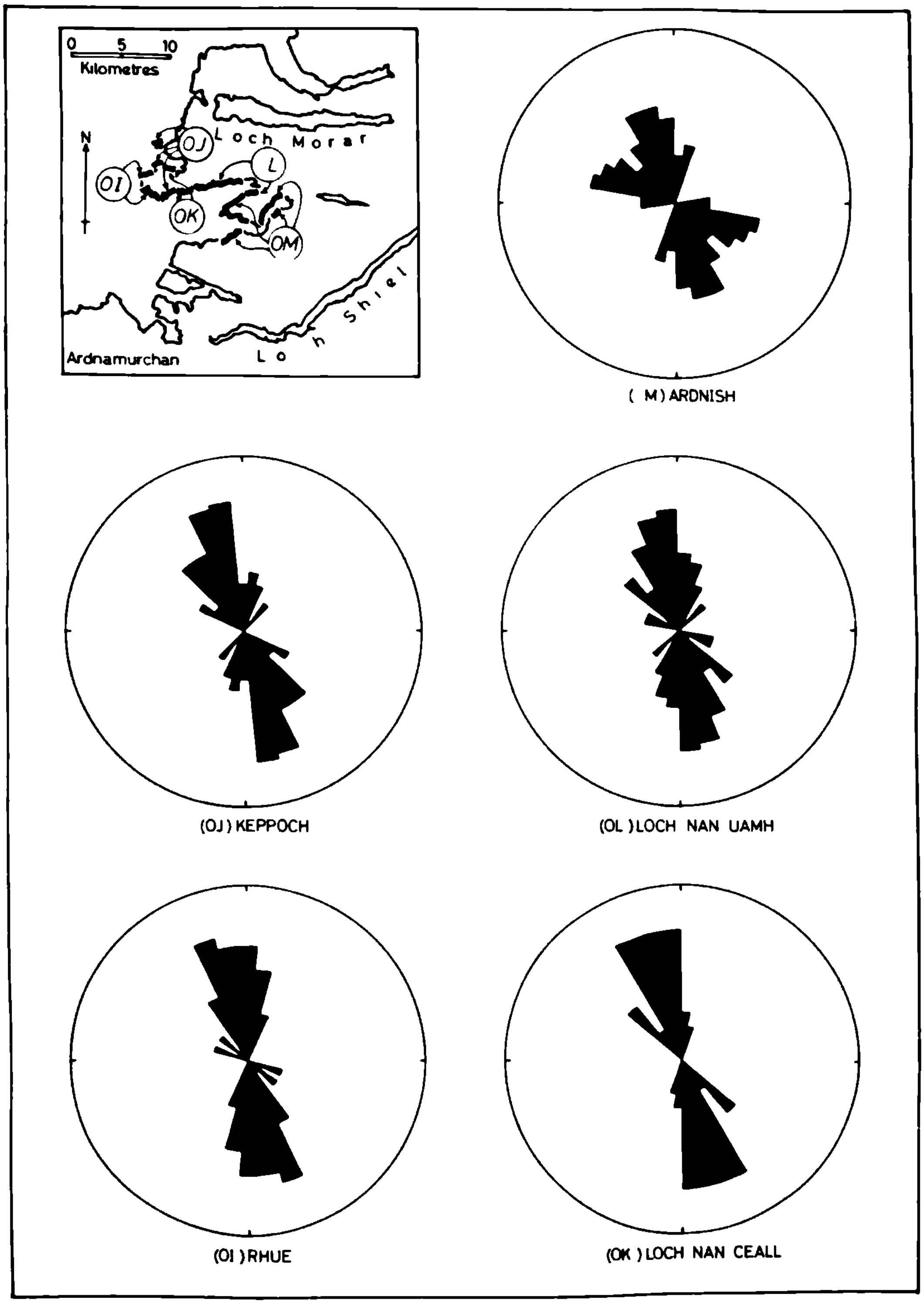


Fig. 29. Trend-analysis

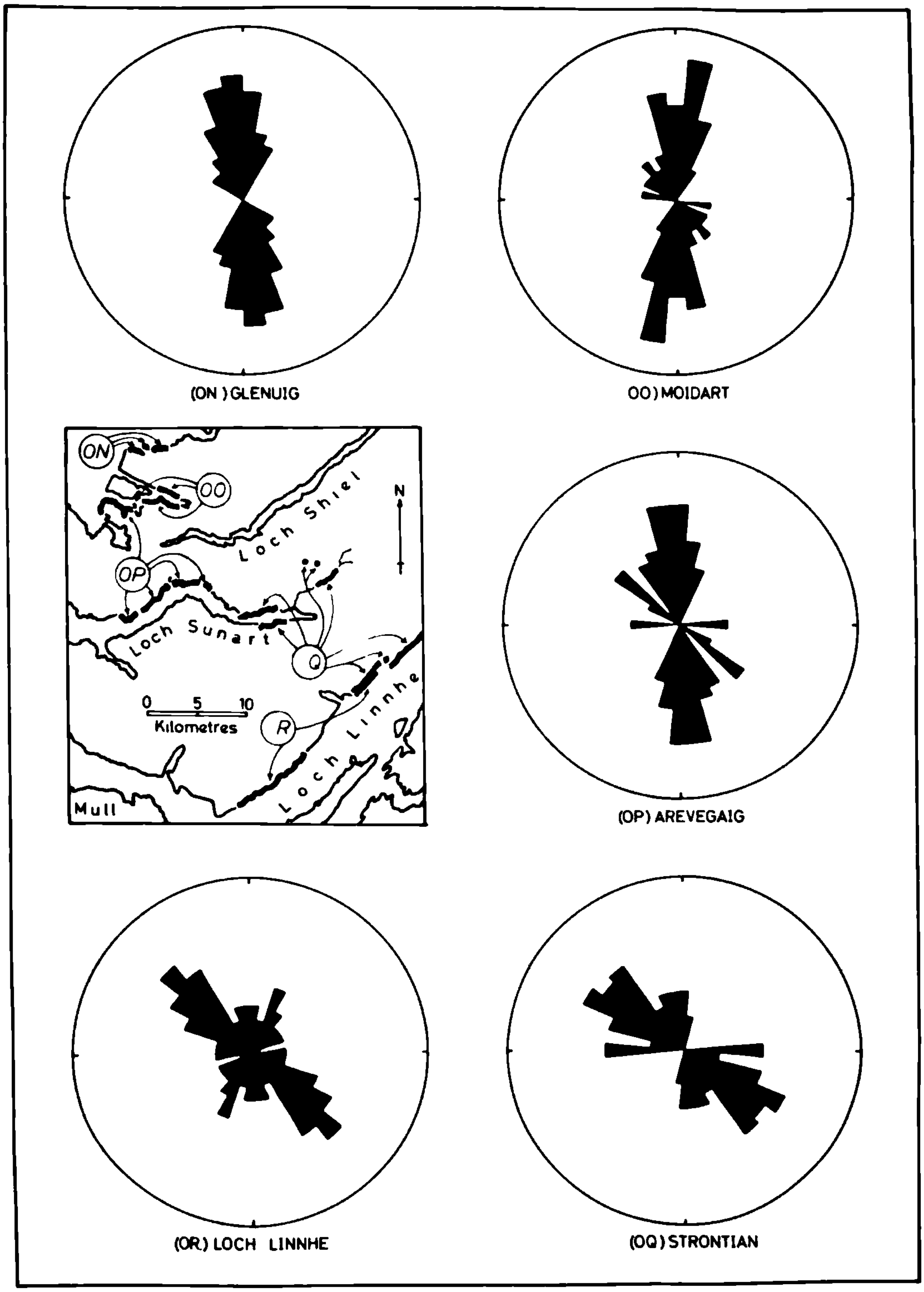


Fig. 30. Trend-analysis

Groups on both the north and south coasts of the Ardnamurchan Peninsula (figs.31 and 32) show a fairly broad and irregular spread of trend, except for groups 'AC' and 'AF'. N. to S. trending dykes form distinctive though often small double-peaks with the more prevailing N.W. or N.N.W. trends.

In summary, the trends of the dykes in the lava-pile of northern Skye, and in Strathaird and southern Skye, average N.N.W., and range but little from this value. Regions close-by and to the east, south and west of the Central Complex show a variety of trends. The trends of the dykes on the mainland are very variable, especially in Knoydart. Elsewhere, except to the very south of the Area of Study, i.e. in Sunart and Loch Linnhe areas, the presence of a N. to S. component is evident. The trends of the dykes in Ardnamurchan are, with certain exceptions, quite variable — more so than the trends of dykes directly to the north and south of the Central Intrusive Complex of Skye.

In order to illustrate more simply the variability of trend throughout the regional linear-swarm, the standard-deviation of the trend for each of the 74 groups is given in Appendix 3. The contour-map of fig.33, based on these values (each plotted at its corresponding group centre-spot), portrays this variability geographically. (The standard-deviation is calculated from the 10-deg. interval ana-

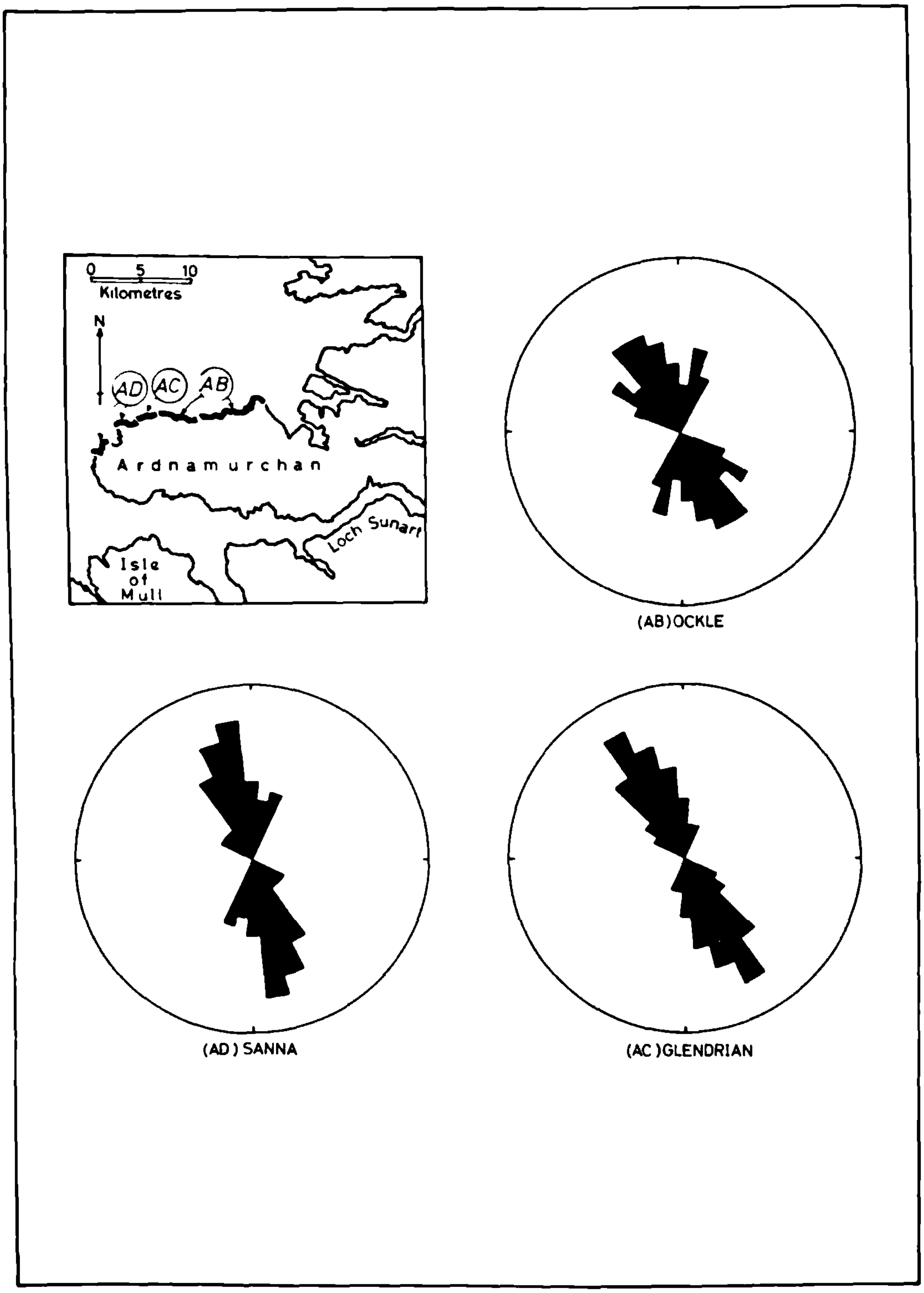


Fig. 31. Trend-analysis

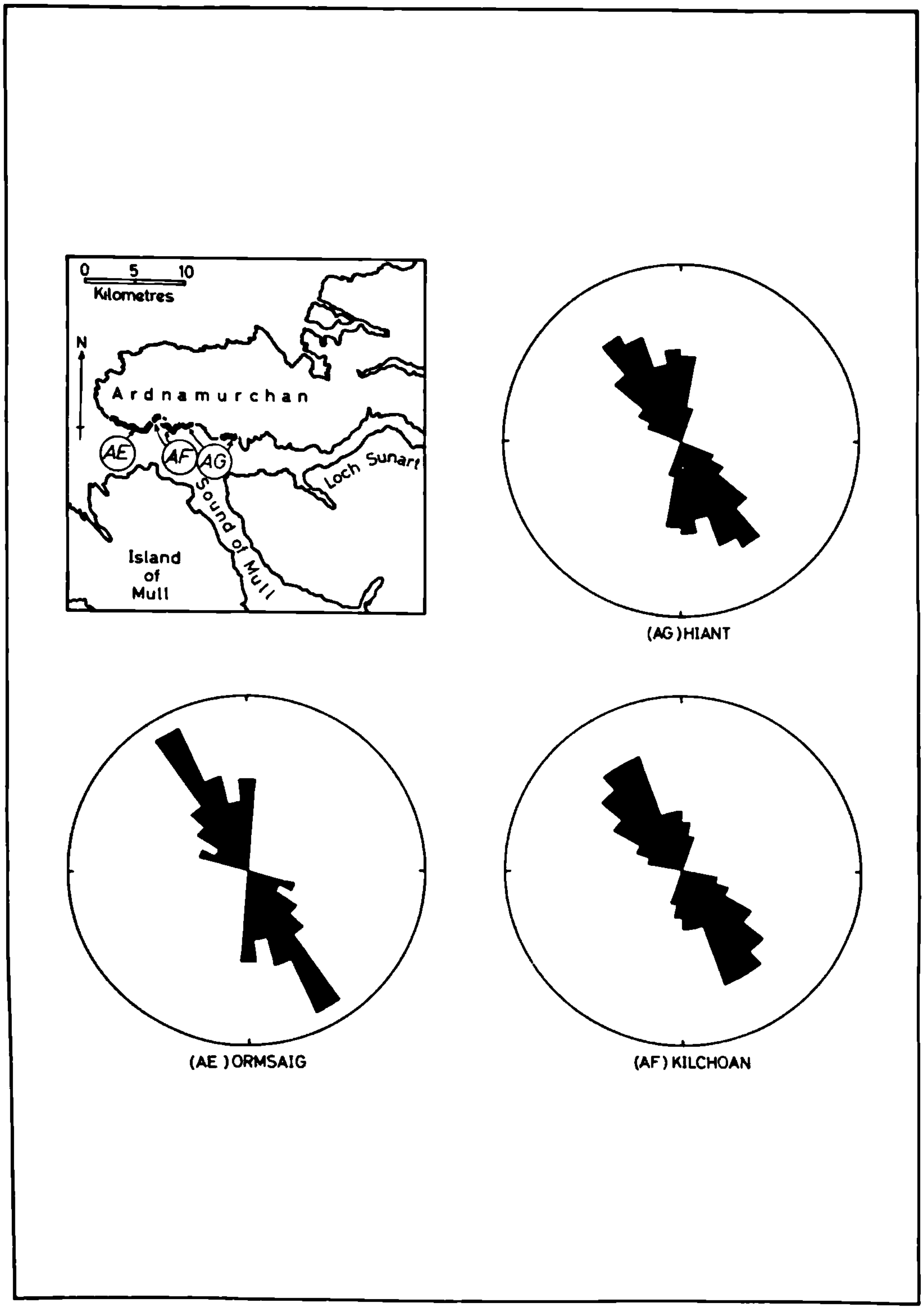


Fig.32. Trend-analysis

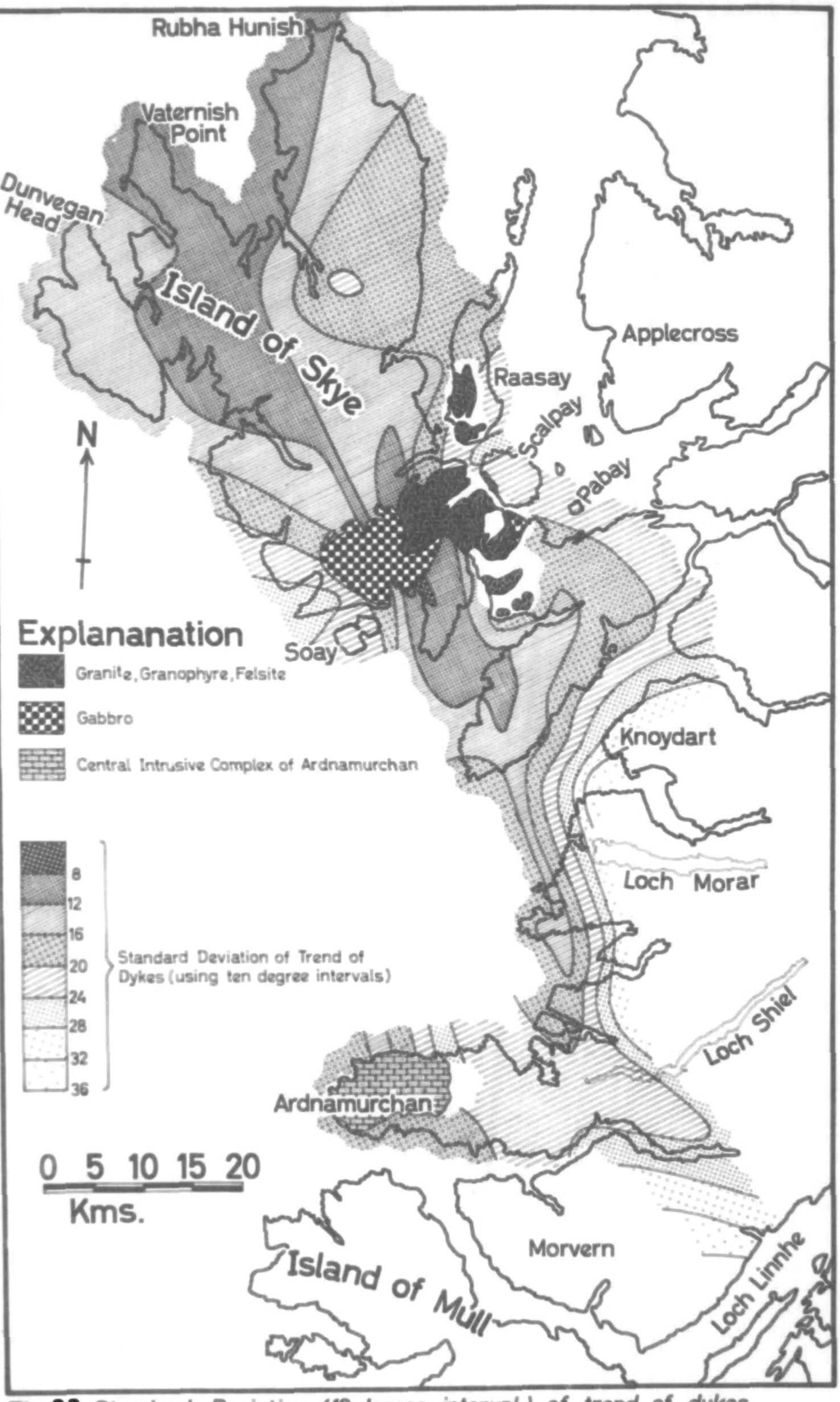


*Fig. **33**. Standard Deviation (10 degree interval) of trend of dykes* lysis in Appendix 6.)

A certain degree of symmetry is observed in the contours of fig.33. The greatest variability of trend occurs in dykes in the Sunart and Loch Linnhe districts. This variability decreases towards the Central Intrusive Complex of Skye, and most rapidly along a N. to S. axis running from Moidart through Arisaig, and N.N.W. through Sleat to Strathaird. In Knoydart the standard-deviation is again high, despite the relative proximity to the Central Complex. In northern Skye a similar axis, trending N.N.W., can be seen. To the south-west and north-east of the Central Complex, variability in the trends of the dykes is again high, despite the exclusion of the trends of dykes of the subswarms. In Ardnamurchan, variability of trend is moderate, though not as low as in comparable regions adjacent to the Central Complex of Skye.

In spite of the fact that arithmetic-averages for the 74 groups have been calculated and used previously in this chapter, such functions are valid only for Gaussian-Distributions of values. The rose-diagrams for these groups indicate how, in many cases, this type of distribution is not found using such small numbers of dykes. Comparison of the arithmetic-mean, median and geometric-mean trends (Appendix 3) also demonstrates this. In a Normal- or Gaussian-Distribution, the arithmetic-mean and median lie within the range of the geometric-mean. Such is the case for a few of the groups, and allocated to the centre-spot of each of these groups (fig.34) is the letter 'N' (for "Normal") (Appendix 3). Groups in which correspondences between the mean values are not found are lettered 'A' (for "Abnormal").

Regions in which "normal-distributions" are found are roughly demarcated and ornamented. It is notable that the areas of "normal-distribution" are largely confined to the terrains occupied by the lava-pile, and to parts of Strathaird, Sleat, and the Broadford Bay district. The extension of the area to Arisaig, across the Sound of Sleat, is uncertain. Further comment on this distribution is made in concluding chapters.

A contour-map of the arithmetic-average trends of the dykes, in combination with a contour-map of the standard-deviation of these trends, portrays the general details of the geographical patterns of trend-distributions. On the other hand, a succession of 74 group rose-diagrams reveals the corresponding specific details. The first is not comprehensive: the second is too precise to be quickly and easily assimilated by the reader. The last diagram (fig.35), in this section on the trends of the dykes of the regional linear-swarm, is an attempt to overcome these problems of presentation of the facts.

This succession of four maps (fig.35) illustrates the

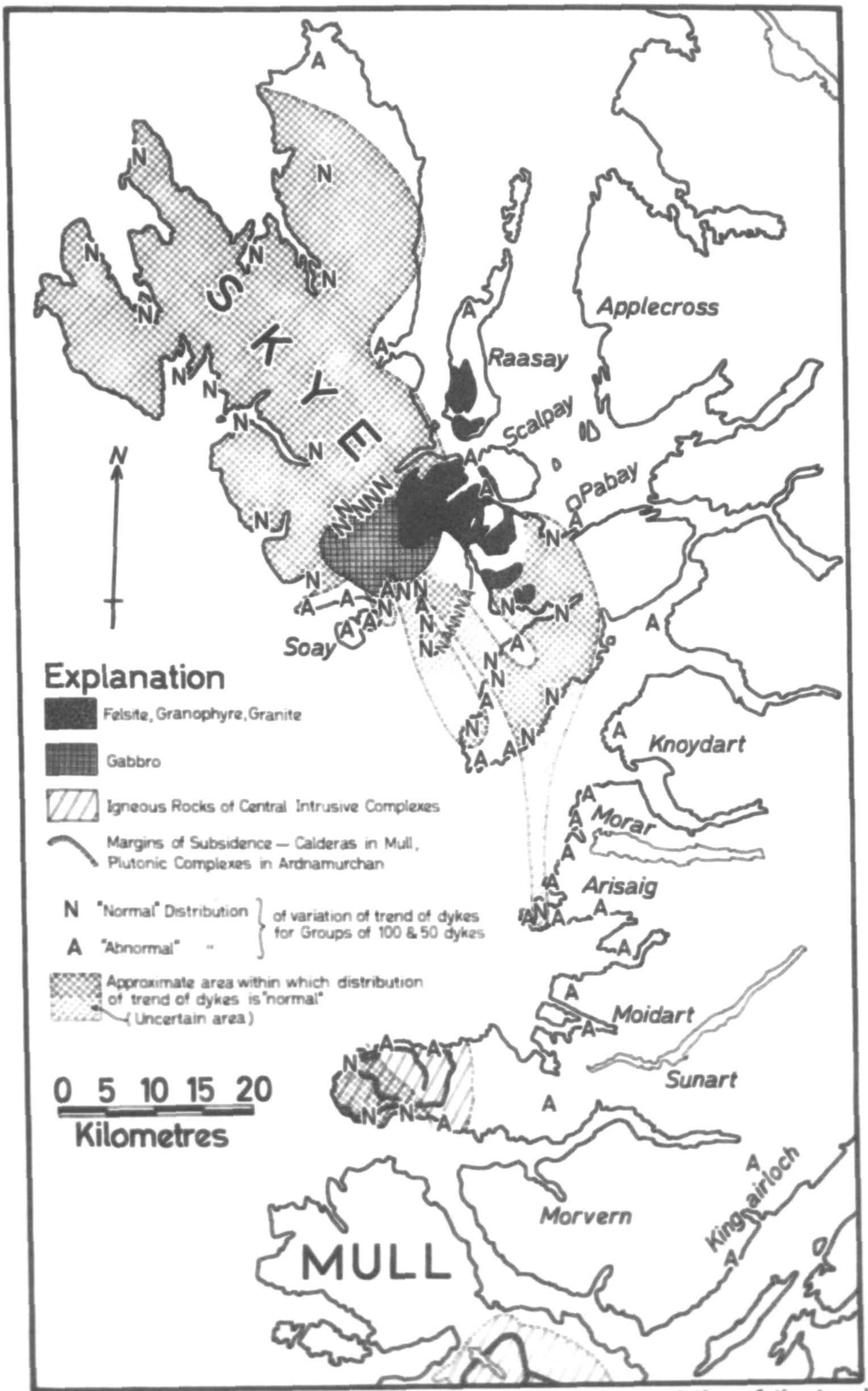


Fig. 34. Map to show approximate areas in which the variation of the trends of the dykes approaches that of a Normal (Gaussian) Distribution.

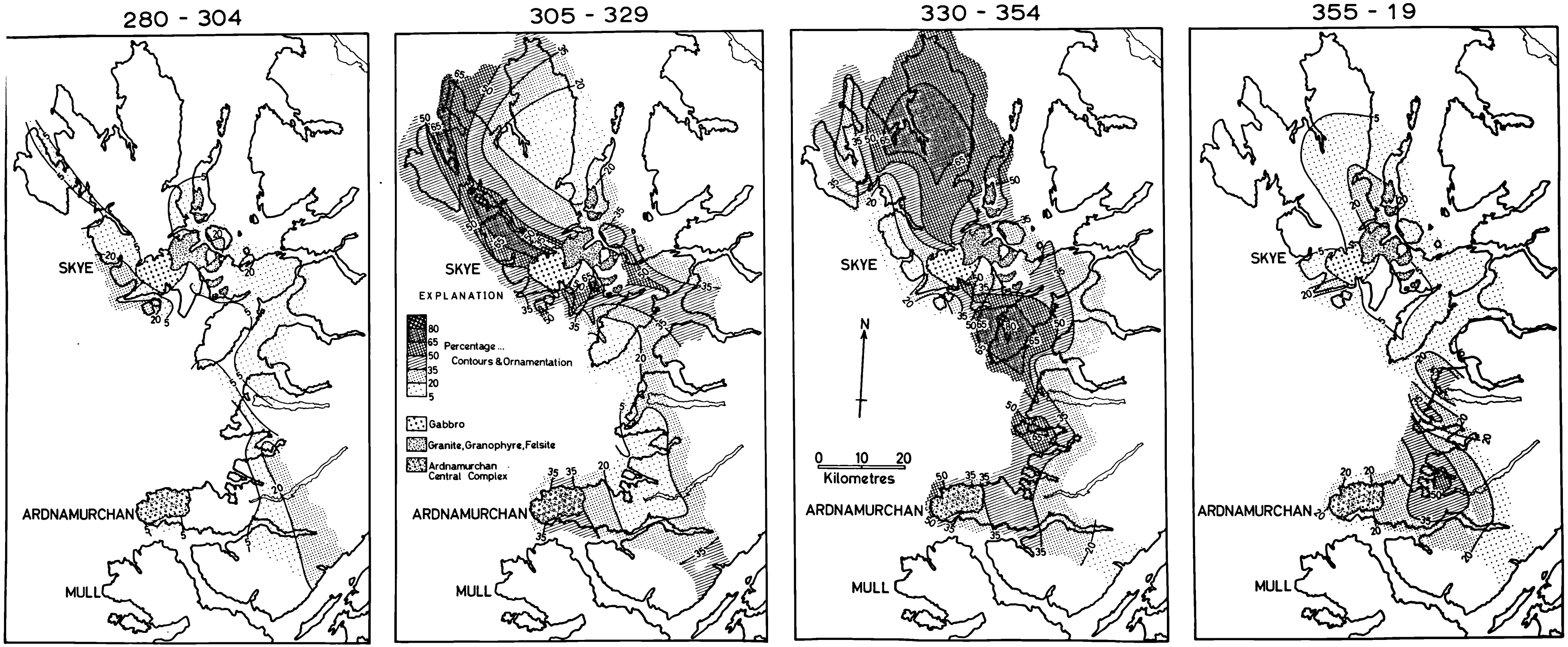


Fig.35. Patterns of Distribution of the various Trends of the dykes

geographical distribution of the dykes of the regional linear-swarm with certain ranges of trend. The ranges chosen are of equal-interval and are: (i.) 280 to 304, (ii.) 305 to 329, (iii.) 330 to 354, (iv.) 355 to 19, each inclusive, and each in deg. of compass. For each of the 74 groups, the value of the percentage-number of dykes which fall within each range is allocated to the respective group centre-spot. These values are used to construct contour-maps with 5, 20, 35, 50, 65, and 80 per cent. levels.

A close inspection of fig.35 clarifies many, if not all, of the important points made in this section on the trends of the dykes of the regional linear-swarm, including, by the comparison of the four maps each with the other, the geographical variation of the standard-deviation of the trend.

6:VI. "Controls" of Trend.

The major controls over the trends of the dykes are discussed in concluding chapters (Ch. 15 & 16). The reasons for variations in the trends of the dykes are inter-related with other properties of the dyke-swarms yet to be discussed. At this stage, however, some observations on the trends of dykes outcropping in the Moine Series in Morar, Arisaig, Moidart, and Sunart, and on the trends of dykes outcropping in certain areas of Torridonian country-rock, can be made without reference to other aspects of the swarms and their properties.

Some of the dykes outcropping in Moinian country-rocks trend parallel to the strike of the foliation of these rocks. This is especially true in districts where psammitic rocks outcrop. Other dykes simply cross-cut the foliation, and are wholly discordant. Yet others possess a zig-zag trend, part paralleling and part cross-cutting the foliation. These features are depicted in a series of field sketch-maps (figs.36a. to f.) as well as photographs (Plates 2, 3 & 4) of several dykes from the Morar district, including multiple and off-set types.

Of all the observed dykes which outcrop in Moinian rocks, whether these be psammitic or pelitic, about one-half are seen to lie parallel to the strike of the foliation, and the other half are seen to cross-cut it and possess a typically N.N.W. trend. In the following paragraphs an attempt is made to analyse this behaviour.

Fig. 37 is a map based on 350 measurements of the strike of the foliation of the Moine Series. These readings were taken during the mapping of sections suitable to the location of the Tertiary dykes. Some information is also taken form the one-inch to one-mile Geological Survey Sheet, 52, Scotland. The strike of the foliation is mainly northerly. Fig. 37 represents a mere outline of the geology of the area.

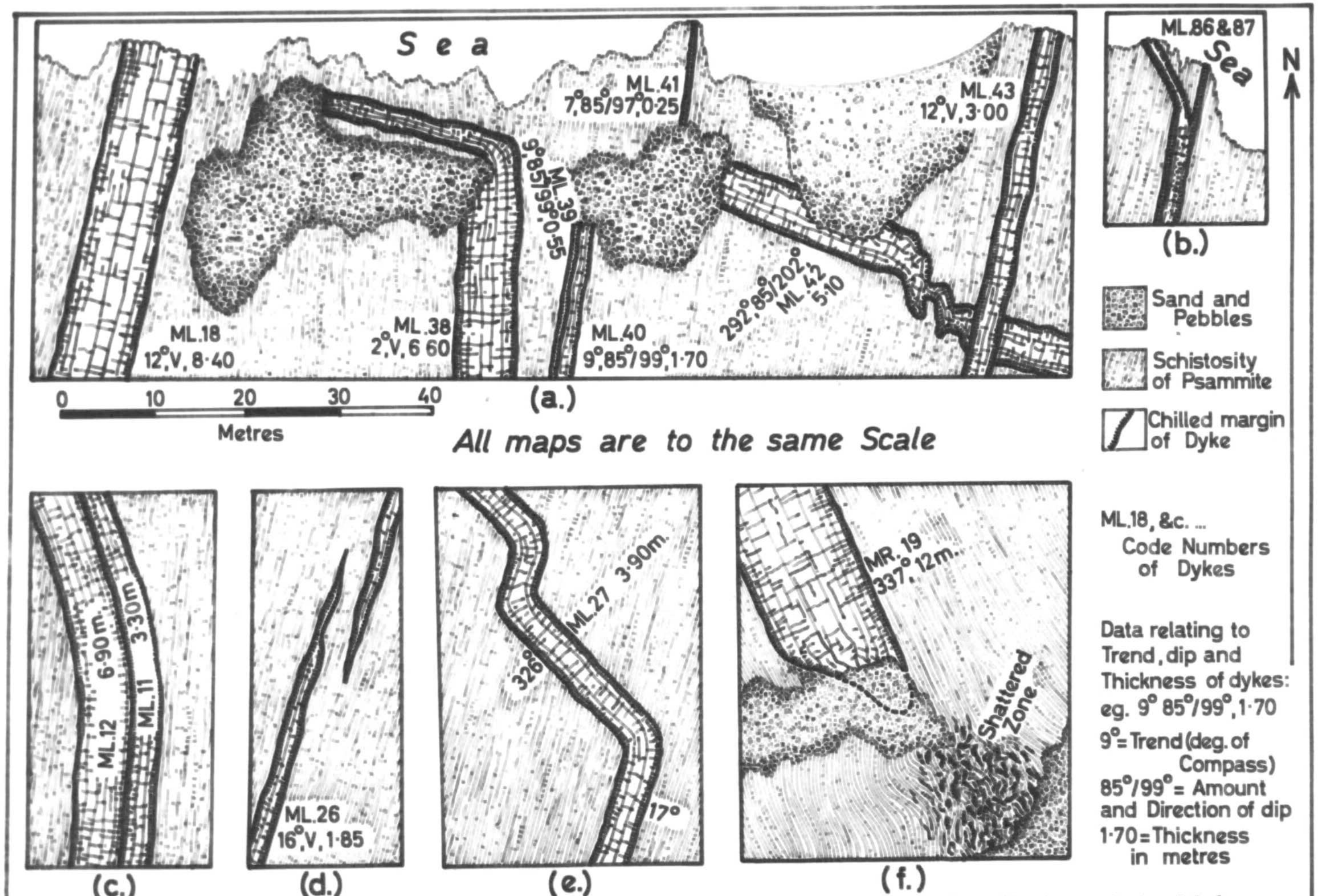
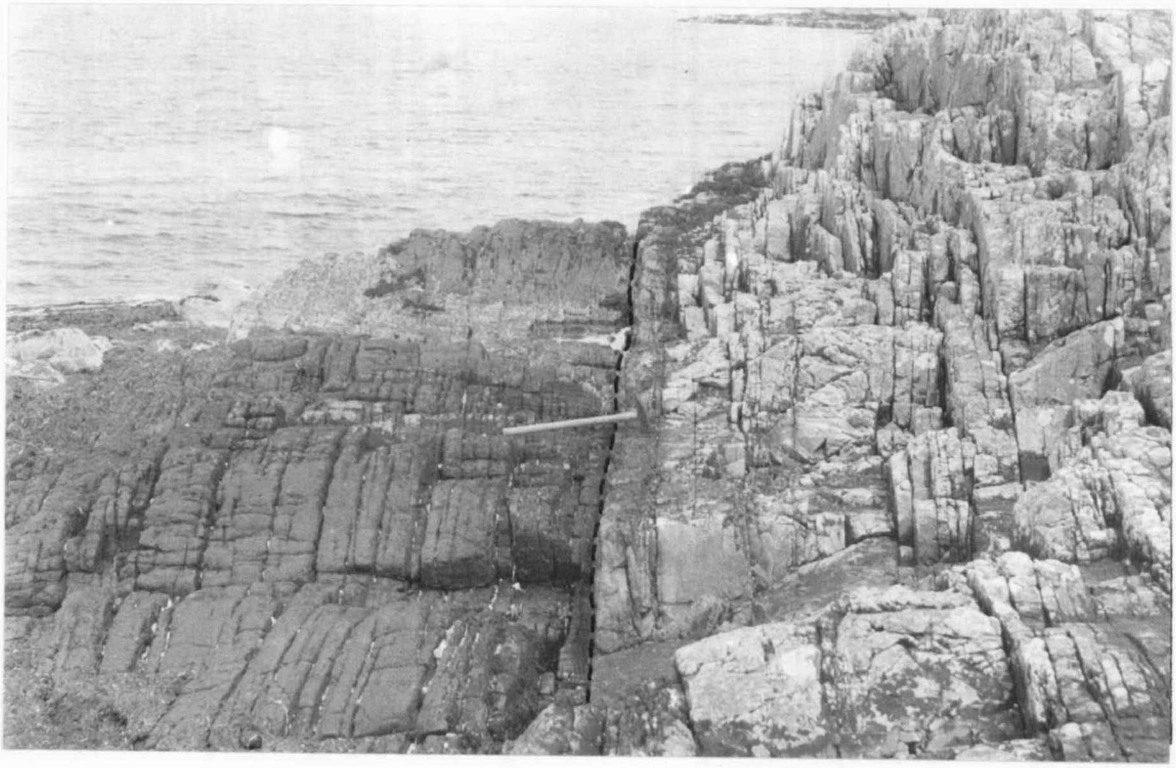


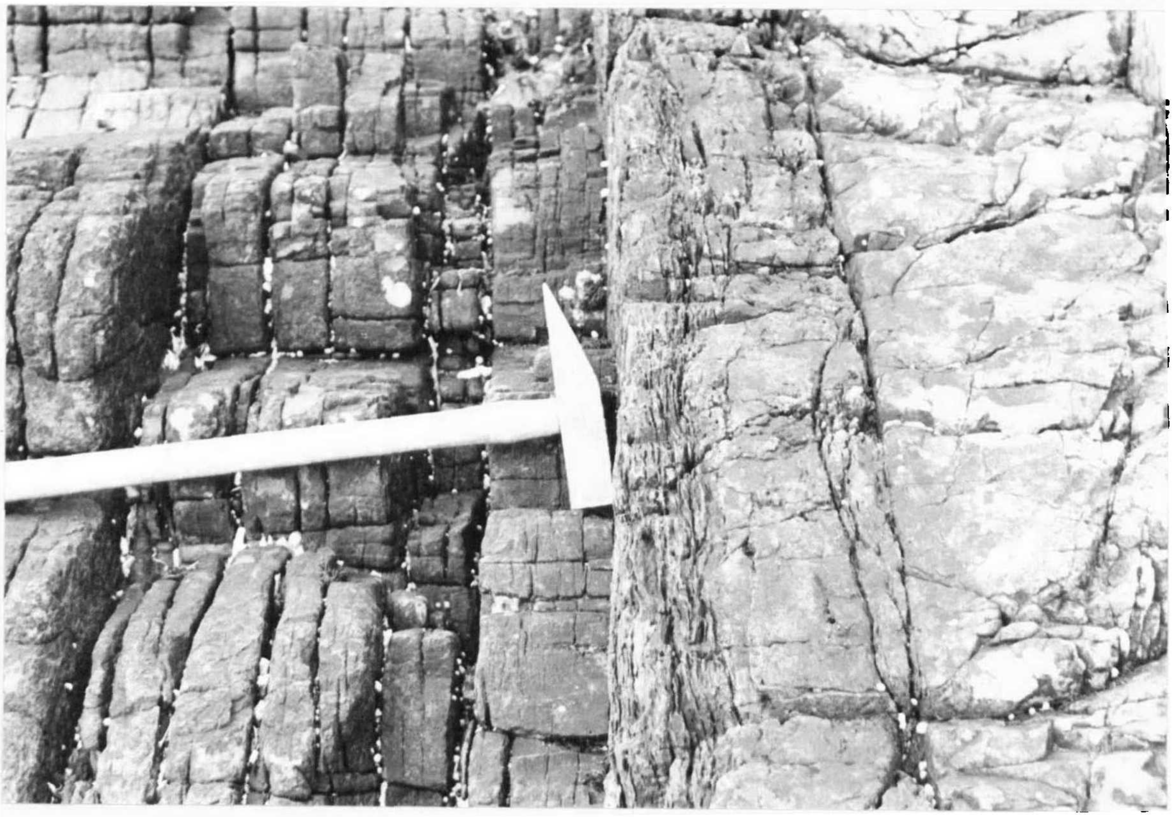
Fig.36. The relationships of the trends of some dykes to the strike of foliation of the Moine.

PLATE 2



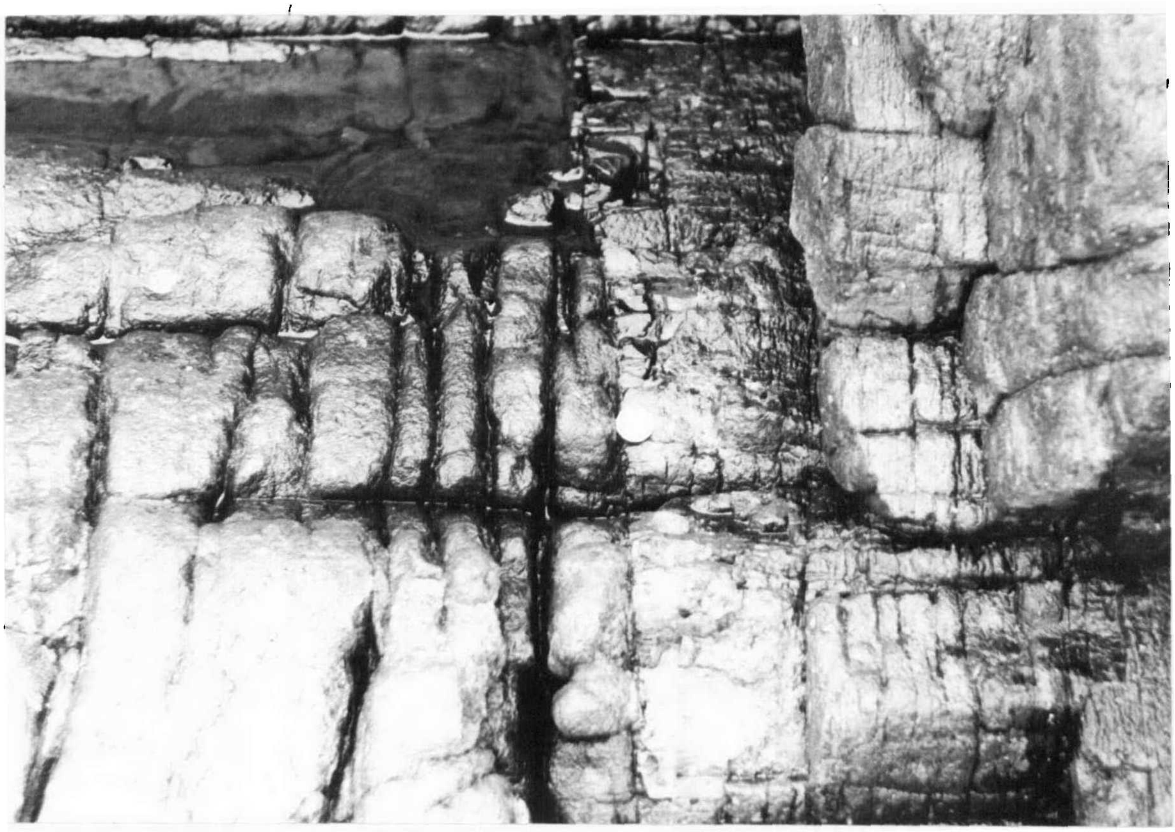
View looking northwards along a N. to S., coarse, dolerite dyke (left of photograph) on the shore near Traigh House (South Morar). The dyke is in contact with Moinian psammite (right of photograph). Both the dyke and the plane of foliation of the psammite are inclined vertically, and the eastern margin of the dyke (located by a broken line) lies parallel to this latter plane. (Length of hammer ca. 0.6m.)

PLATE 3



Closer view of the contact between the dyke (left of photograph) and Moinian psammite (right) illustrated in Plate 2. The finely spaced joints in the psammite adjacent to the dyke are indicative of the baking resulting from the emplacement of the latter.

PLATE 4



The contact between the dyke (left) and psammite (right) of Plate 2 at some other locality than that of Plate 3. Intensely baked psammite near the contact. (Size of coin : 0.03m. diameter.)

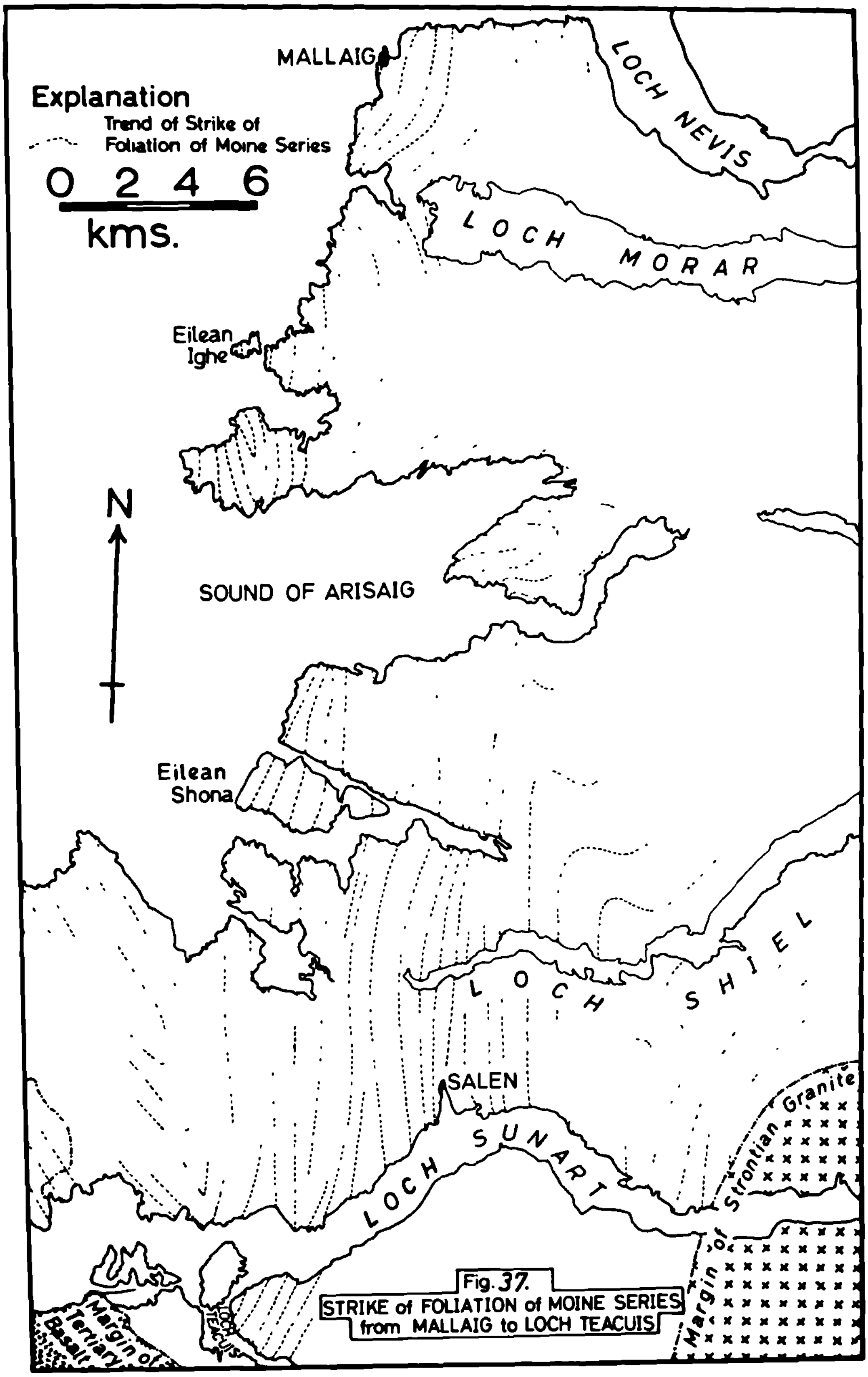


Fig. 37.
STRIKE of FOLIATION of MOINE SERIES from MALLAIG to LOCH TEACUIS

Appendix 7A gives the proportion of dykes which are, at the observed outcrops, parallel to the strike of the foliation of the Moine, whether or not they lie parallel to the dip, too. The arithmetic-average trends of these dykes, and of those dykes which show cross-cutting relationships, are plotted as bars, proportional in length to the numbers of dykes involved, at the group centre-spots (fig.38). This demonstrates that the trends of cross-cutting dykes are towards N.N.W., and the trends of the parallel dykes are towards N.

In areas where the strike of the foliation of the country-rock is to the north-east, the proportion of cross-cutting dykes is markedly increased, e.g. on the sections north and east of the Sound of Arisaig. Only groups, in which all 50 of their constituent dykes outcrop in Moinian rocks, are used in the construction of fig.38.

Fig.39 (based on the data of Appendix 7A) illustrates a fuller analysis of the trends of the dykes in each of the twelve groups. The rose-diagrams are of the equal-area type, with outer circle at 50 per cent. They serve to illustrate that the trends of those dykes which cross-cut the foliation are generally towards N.N.W., with some exceptions, and that the more northerly trending dykes are those which parallel the foliation.

Taking the data (Appendix 7A) on all of the outcrops

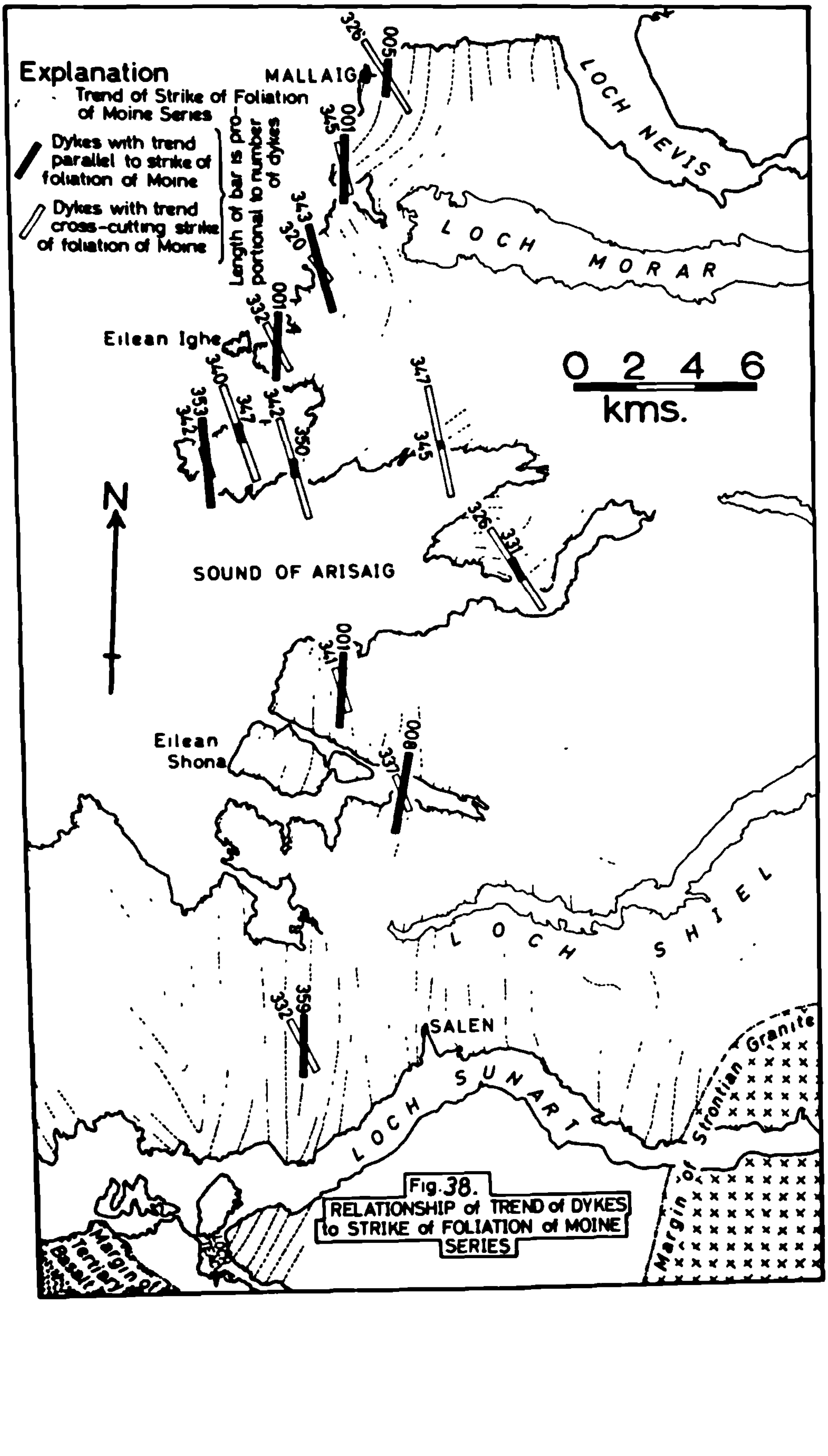


Fig. 38.
RELATIONSHIP of TREND of DYKES to STRIKE of FOLIATION of MOINE SERIES

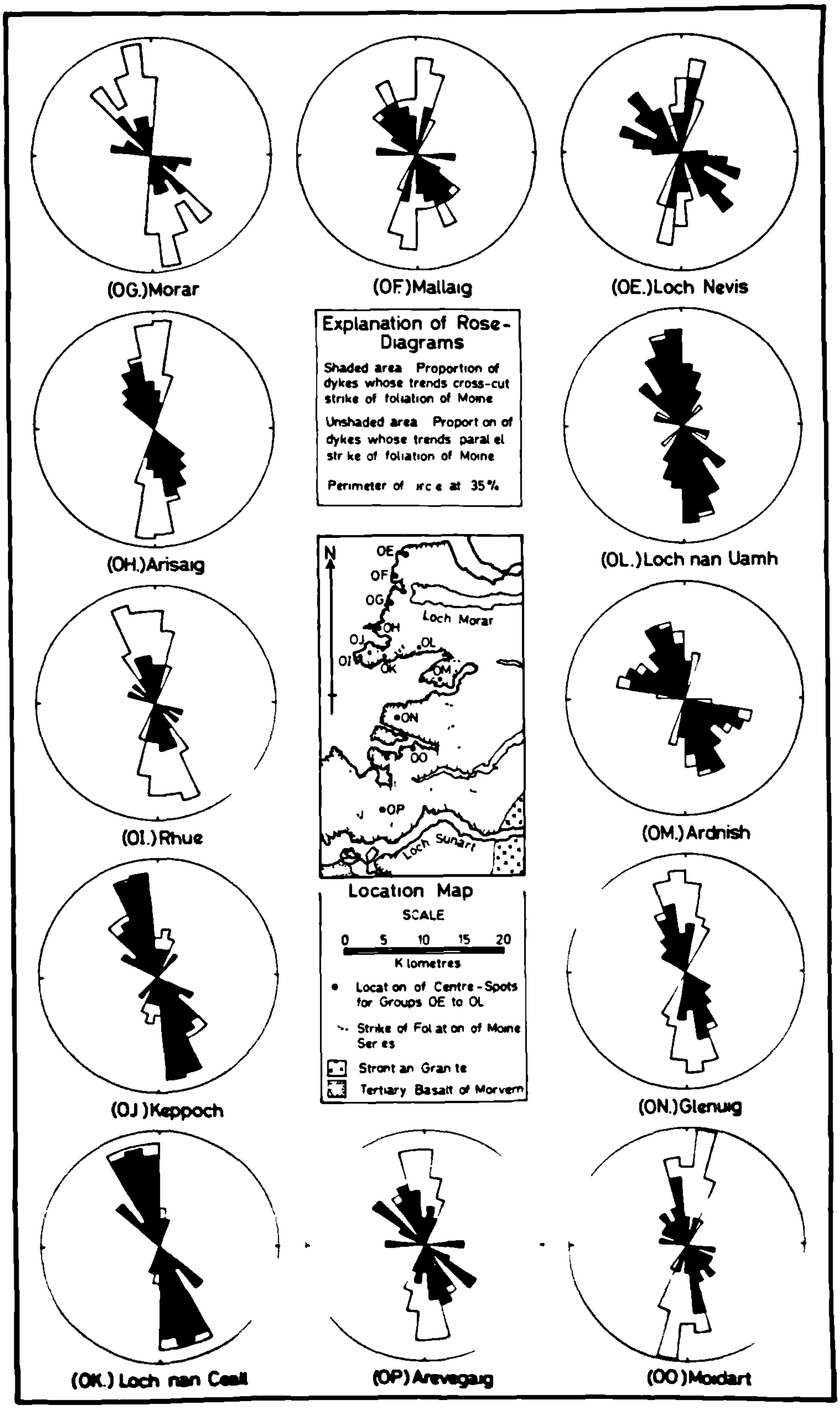


Fig. 39. Group-analyses of the trends of the dykes outcropping in Moinian country-rock

of dykes observed in the area of Moinian country-rock (645 dykes), and plotting the frequency-distribution of their trends (fig.40a.), it is found that the peak of the histogram lies in the range 350 to 360 deg. of compass. The peak for dykes which parallel the strike of foliation (fig.40b.) is at 360 to 10 deg. of compass. The peak for those dykes which cross-cut the foliation is 340 to 360 deg. of compass (fig.40c.). Fig.40d. shows the ratio of the numbers of parallel and cross-cutting dykes. This rises steeply towards a maximum value between 10 and 20 deg. of compass.

Some dykes outcropping in well-jointed Torridonian strata trend parallel to the strike-slip joints in these beds. This is an especially prominent feature of dykes in Raasay and Soay, but is very infrequently shown by dykes elsewhere in terrains of Torridonian country-rock. The dykes in Raasay and Soay zig-zag, side-step, etc.,in similar fashion to the illustrated examples in the Moinian country-rocks. Fig.41 (A. and B.) and Plate 5 illustrate the main types of field-observations of structural relationships.

Appendix 7B is an analysis of the trend of the dykes in groups of 50, on Raasay and west Soay, and a group of 100 dykes covering the remainder of Soay. The arithmetic-average trends of those dykes which cross-cut, and those which lie parallel to, the strike-slip joints, are approximately the same. Moreover, the average trends of groups of

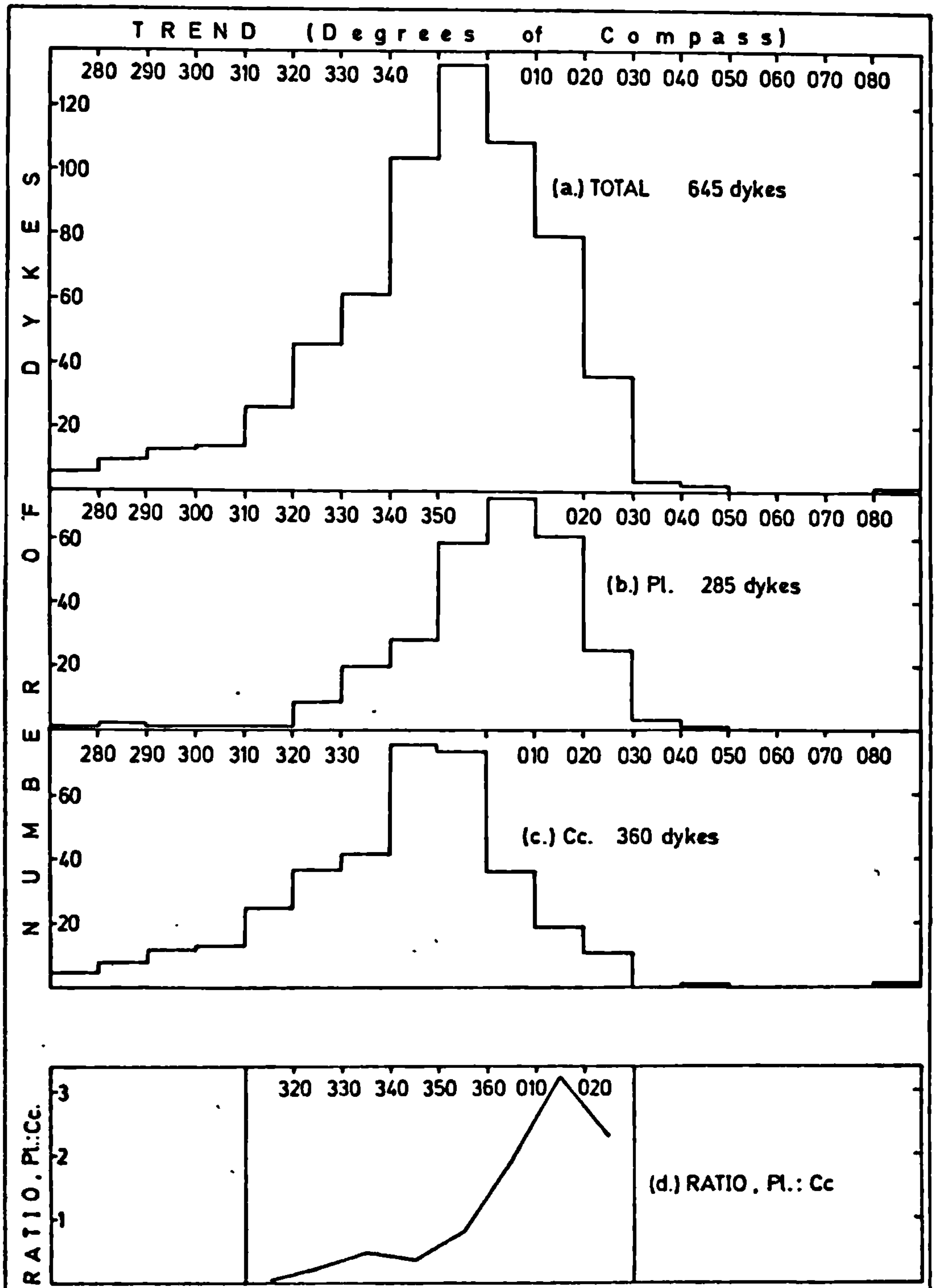


Fig 40 Dykes with trends parallel to or cross-cutting strike of foliation of Moine Series

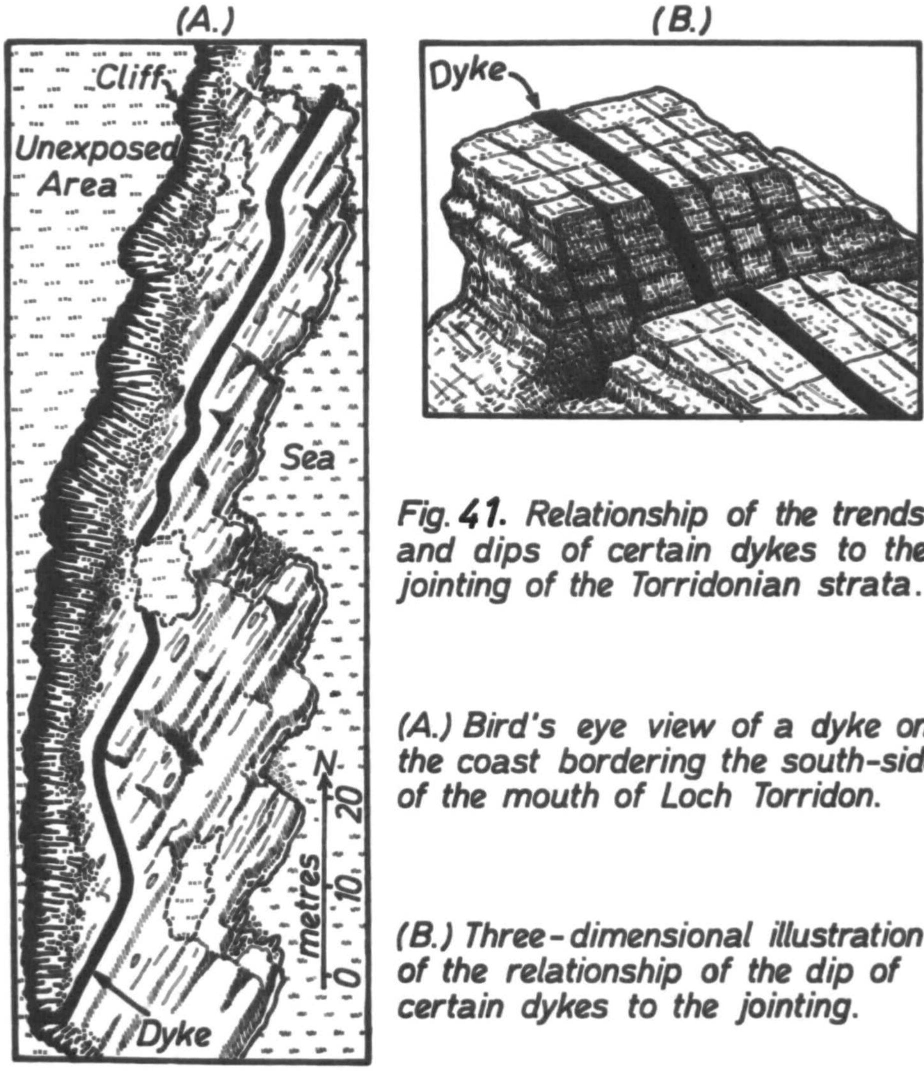
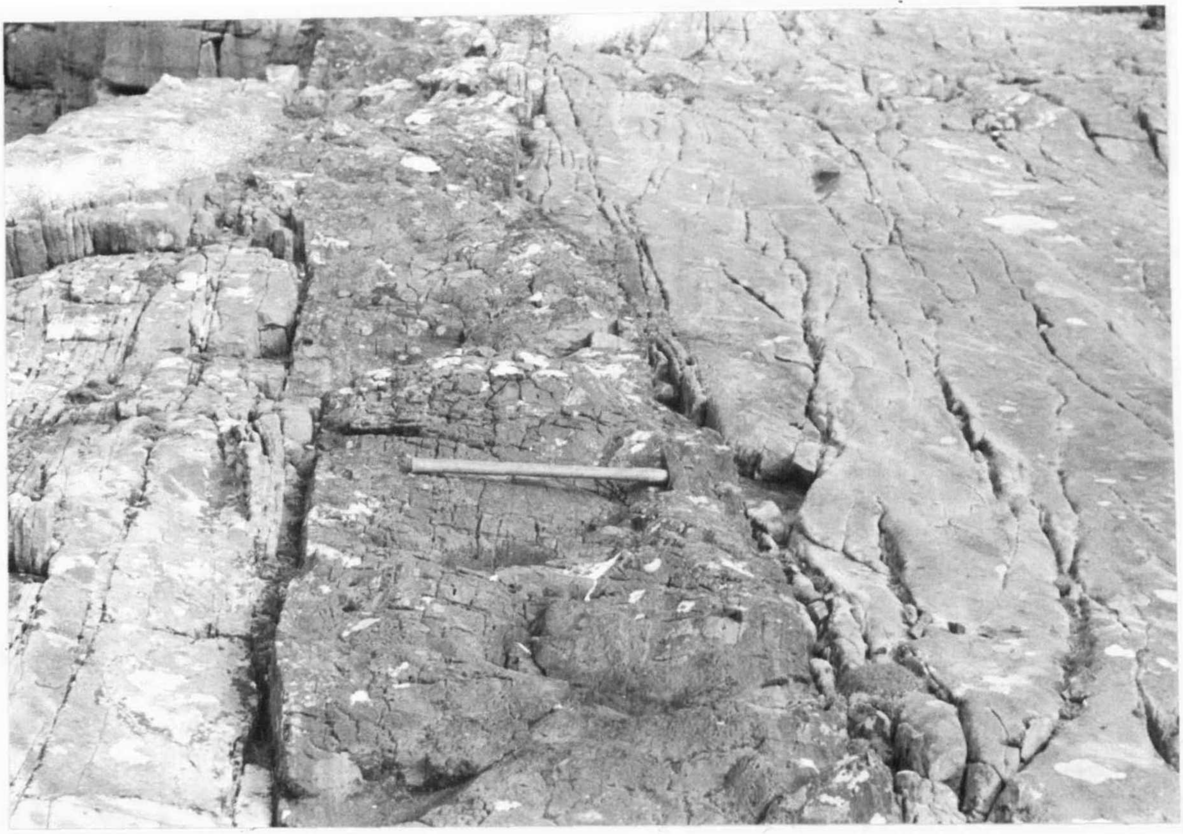


Fig. 41. Relationship of the trends and dips of certain dykes to the jointing of the Torridonian strata.

(A.) Bird's eye view of a dyke on the coast bordering the south-side of the mouth of Loch Torridon.

(B.) Three-dimensional illustration of the relationship of the dip of certain dykes to the jointing.

PLATE 5



View looking south-eastwards along a N.W. Tertiary dolerite dyke on the coast north-west of Beinn Bhreac (N.E. part of Island of Soay). The dyke is intruded along the plane of strike-slip jointing in a Torridonian grit. The surface of the Torridonian rock is a shallow-dipping bedding-plane. The observation of the almost vertical strike-slip joints is made easy because of processes of differential erosion. (Length of hammer : ca. 0.6m.)

dykes adjacent to the three groups '0A', '20' and '0B', e.g. '5A' and '5B' for Raasay, '19A' for Soay, and '22' for west Soay, are very similar to the corresponding averages for the three groups (Appendix 3). These facts demonstrate that perhaps the jointing of the Torridonian rocks has less control over the trend of the dykes than is at first apparent. The coincidence of a dyke with a strike-slip joint in the country-rock of Raasay and Soay could be a chance coincidence, with by far the greater influence on the trend arising from those major controls yet to be discussed.

Kaitaro (1952) explained that the surface expression (outcrop-pattern) of primary offset or a zigzagging (contemporaneous with dyke-emplacement) may apparently be the same as that due to secondary offset or zigzagging due to faulting (post dyke-consolidation). Primary zigzagging and offset or en echelon structures, oblique or normal to the trend of the dyke, are produced by (i.) simple splitting of a dyke at depth, especially favoured by conditions of shear (E.M. Anderson,1951,p.55; Gilliland,1963), (ii.) slipping normal to the dyke-margins, (iii.) vertical movements in the plane of the dyke, (iv.) rotational movements in the plane of the dyke.

Of those Tertiary dykes in Skye and Ardnamurchan which exhibit offset this feature is primary, with no evidence of faulting observed in the country-rock, although the exact nature (i. to iv.) of the mechanism was unfortunately not observed. Confirmatory evidence of the primary character of the offsets is found in the chilling of the entire perimeter of each offset component. The contact planes of a dyke with an oblique fault would not be thus chilled. In one case only (fig.36f.) is there evidence of partial secondary movement, exemplified by the shattering of the country-rock.

6:VII. Trends of the Dykes of the Subswarms.

To complete the description of the trends of the dykes, some additional comments on the three subswarms of Skye are made below.

Fig.42 shows three rose-diagrams, representing analyses of the trends of the total number of outcrops of dykes in each subswarm. The frequency-distributions are reduced to a percentage-basis (Appendix 8) : for the Scalpay-Subswarm this is somewhat of an exaggeration since only 39 outcrops are recorded. Each rose-diagram is plotted on an equal-area net, with the outer circle at 50 per cent.

The Scalpay- and Glenbrittle-Subswarms show a marked predominance of N.E.-trending dykes. The former is near-Gaussian in distribution; the latter shows a marked double-peak of N.E. and E. to W. trends. The geographical distribution of these E. to W. dykes is fairly random, although there is a slightly higher proportion of them at both the

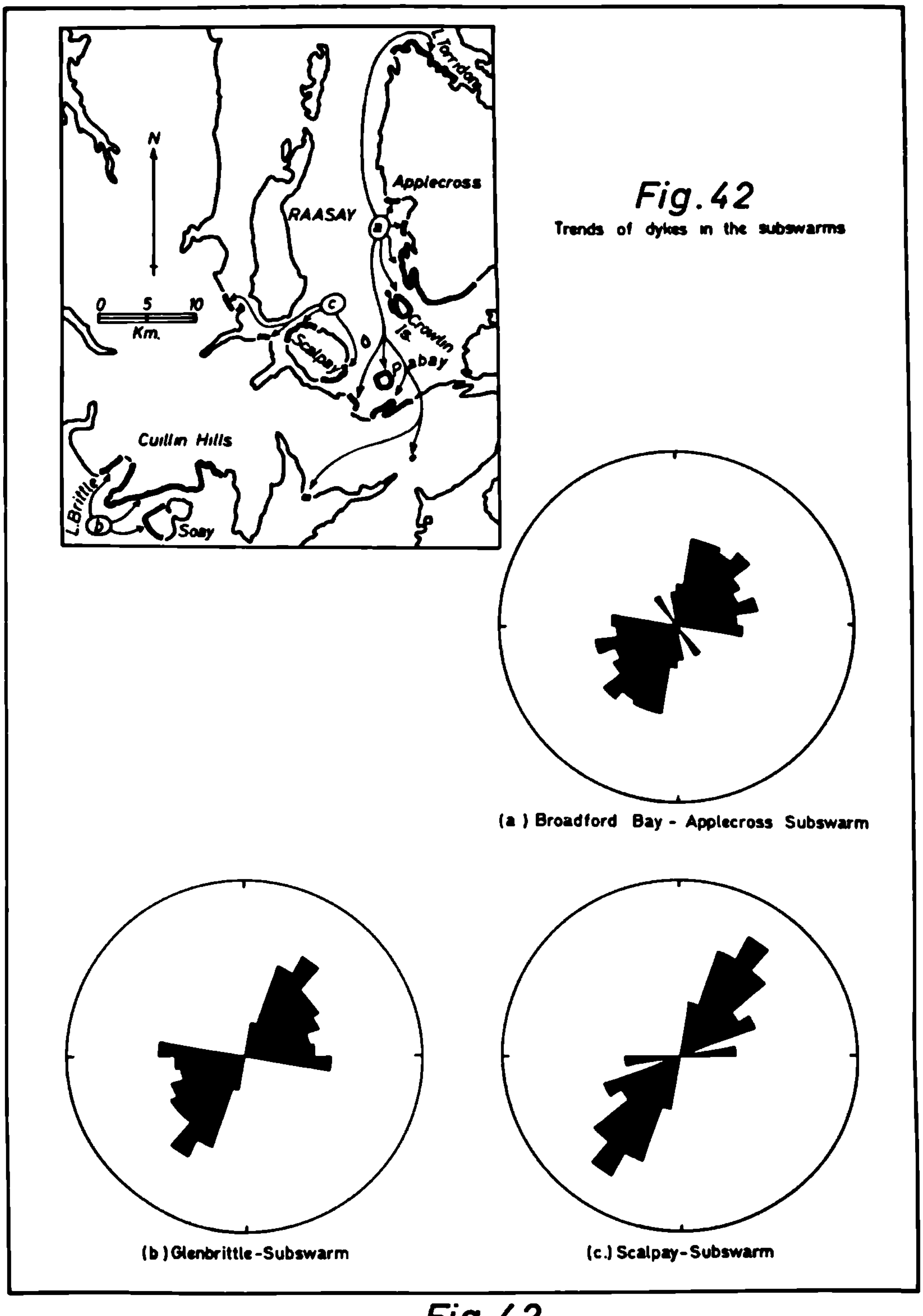

L. Torridon
Applecross
RAASAY
N
0 5 10
Km.
Crowlin Is.
Pabay
Scalpay
Cuillin Hills
L. Brittle
Soay
Fig. 42
Trends of dykes in the subswarms
(a) Broadford Bay - Applecross Subswarm
(b) Glenbrittle-Subswarm
(c.) Scalpay-Subswarm

Fig. 42

head of Loch Brittle and on the coast of Skye directly to the north of the extreme eastern point of Soay (also fig. 11). In these two locations, some of these E. to W. dykes may be of radial and concentric (or tangential) types, respectively.

The overall average (arithmetic) trends for the Scalpay- and Glenbrittle-Subswarms is about due N.E. (Appendix 8). The same applies to the dykes of the Broadford Bay-Applecross Subswarm, although the frequency-distribution of their trends is of very broad spread, and yet not characterized by a double-peak. If sampling throughout the Broadford Bay-Applecross Subswarm is random, then this lack of a double-peak illustrates the smoothness of the change in average trend from Rubha Suisnish to Loch Torridon.

The dykes of the Broadford Bay-Applecross Subswarm outcropping in Torridonian strata are very infrequently observed to lie parallel to the strike-slip joints of the beds. This further emphasises the point that the control of the structures in the Torridonian is apparently of a minor character.

6:VIII. Concluding Remarks.

The above detailed description of the behaviour of the trends of the dykes cannot be summarized easily. Each and every aspect of this behaviour is of a significance which, as previously mentioned, is best appreciated upon correlation with the characteristics of the other properties of the dykes(Ch.13).

Chapter Seven

DILATION or CRUSTAL-EXTENSION DUE TO THE DYKE-SWARMS

7:I. Introduction.

It was stated by Richey (1939,p.394) that, "The widely distributed dyke-fissures of Scotland indicate the way in which regional crustal stresses were relieved during periods when deep-seated magma was available for intrusion". As early as 1819, MacCulloch (1819,p.398, vol.1), writing about the Tertiary dykes ("trap veins") of Skye, said, "Whatever proportion, collectively taken, they may bear in breadth to the lateral dimension of the strata which they intersect, it is plain that the whole mass of strata must have undergone a lateral extension equal to that quantity". As recently as 1968, Clifford (1968,p.93) expressed his opinion that "large discordant dike swarms and their attendant flows indicate tensional forces due to motions in the mantle".

For many years the concept of tension within crustal-layers, the belief that these layers consequently fracture and form fissures which are filled by magma from below, and the view that the dykes thus formed are a measure of the crustal-extension (or dilation) resulting from this tension, have been held to be valid by numerous authorities.

In its conventional sense, the term "dilation" refers to that function expressed by the equation:-

$$\text{Dilation} = \frac{\text{Aggregate thickness of dykes in a section}}{\text{Length of the section}}.$$

This fraction is normally converted to a percentage. The length of the section is itself inclusive of the dykes within it. The function is perhaps better expressed by the equation:-

$$\text{Dilation} = \frac{\text{Aggregate thickness of dykes in a section}}{\text{(Length of section)} - \text{(aggregate thickness of dykes in the section)}}.$$

This second expression is a representation of the increase of the original length of section.

However, partly because tradition is importunate, and partly because of the relatively simpler procedure involved in calculations, the former conventional notion is adopted. The values so obtained are perhaps more aptly described as proportions of the aggregate thickness of dykes to unit-length of present-day section. These values bear some relationship to the values derived by use of the second equation, above, but are not as interchangeable with the concept of stretching from an original to a greater length. There is, however, one advantage to the use of conventional dilation, and that is, despite all the implications of the word, this method of calculation does not presuppose that any crustal-extension has taken place. It is simply and wholly a measure of what is seen today, independent of assumptions concerning mechanisms of formation.

Nevertheless, the author believes that the mechanism of formation of the Tertiary Hebridean dykes is one which involves crustal-extension. There is little alternative but to corroborate Richey's words (1939,p.396): "the fact is well ascertained that dykes, normally, are filling fissures, the walls of which have been merely prised apart and have not been displaced relatively to one another in the manner associated with faulting. Any minor irregularity on one side of a dyke has its counterpart on the opposite wall. If the dyke could be removed, the two walls would fit together as exactly as two pieces of a torn paper".

There are convincing descriptions of non-dilational dykes, i.e. those formed by processes of replacement. As examples may be quoted the work of Billings (1925) on the Medford Dike in eastern Massachusetts, and King (1948) on the aplite and pegmatite dykes and veins in an area in Nigeria. One of the chief criteria used to confirm dilational emplacement is the off-setting, in an appropriate direction and of suitable distance, of pre-existing structures in the country-rock, which lie at an oblique angle to the strike of the dyke. Perhaps, in this respect, intersecting dykes are the most useful. Goodspeed (1940) gave a list of petrographical and field criteria which may be used to distinguish dilational and non-dilational dykes. On the lines of evidence in the latter set of criteria, most of the indications in the Area of Study point to a dilational mode of emplacement. There are some rare examples, demonstrated by intersections of dykes, where there may have been a component of shear in the formation of a fissure. Evidence from the majority of dykes confirms that there is no possibility of an origin by replacement. Whether the dykes are considered to be of an active or passive nature, i.e. whether they wedged their way upwards as E.M. Anderson (1951) postulated, or whether the magma flowed up a pre-formed rent in the crust, the calculation of the value of dilation is unaffected.

7:II. Examples of Previous Calculations of Dilation.

Tyrrell (1928,p.249) demonstrated that in the 14.8 miles (measured in a N.E. to S.W. direction) of coast on the south and east of Arran, there are outcrops of 525 dykes, of total thickness 6050 ft. He calculated that this is equivalent to stretching in an E.N.E. to W.S.W. direction of 5410 ft. in 14.4 miles of originally unstretched crust. There are many arguments which can be levelled at this and the calculations of other workers, most notable among which is, as far as their writings indicate, an apparent disregard of the degree of exposure in the traverses studied.

Bailey (1924,p.360) gave corresponding figures for the Mull-Swarm as 375 dykes, of total width 2504 ft., in 12.5 miles. Richey (1939,p.422) gave his calculations, using these figures, of the "proportion of breadth of section occupied by dykes", for the Arran and Mull Swarms, respectively, as 7 and 4 per cent.

Other examples of similar calculations have been presented for dyke-swarms throughout the world. Paramount among these, as far as this work is concerned, are three pieces of work by G.P.L. Walker, from which germinated the idea that the crustal-extension of the Hebridean swarms could be represented by graphical or contouring techniques. In other words, not only the total, but also the rate of change of, dilation across a dyke-swarm could be illustrated diagrammatically. By studying the number and aggregate thickness of Tertiary dykes in well-exposed sections, G.P.L. Walker (1959B,1960) analysed the distribution of these dykes in two swarms of eastern Iceland. Estimates of the percentage crustal-stretch over the eastern part of the Antrim Basalts led G.P.L. Walker (1959A,p.181) to produce a tentative distribution-map, indicating by contours the intensity of the Antrim-Swarm of northern Ireland.

7:III. Deliberations on the Method to be Used.

The dilation is calculated as the aggregate thickness of dykes per unit length of section, this length being computed in an E.N.E. to W.S.W. direction. This particular direction is chosen because the arithmetic-mean, the median, and the geometric-mean trends of the dykes for the whole assemblage of data is roughly N.N.W., i.e. at right-angles to E.N.E. to W.S.W. The greatest variation, within the regional linear-swarms, from this trend is found among the dykes of Morar and Moidart.

It is theoretically possible to vary the direction in which the length of a section is computed, to lie at right-angles to the average trend of the dykes in that section. The drawbacks to this are twofold:-

(i.) A traverse of considerable distance near the limits of the swarm, where intensities are low, may contain the outcrops of very few dykes. The arithmetic-average value of the trend of such small numbers is statistically meaningless, especially if the spread of the trend of these few dykes is very large, as is often the case near the limits of the swarms.

(ii.) The arithmetic-average trend for a large number of dykes, in a section where intensities are high, may have some meaning, especially where the distribution of the trends is Gaussian. However, dilation is concerned with the aggregate thickness of the dykes. Surely the need, therefore, is for a "weighted" average trend, such that any computation of this average, for a number of dykes, acknowledges that the trend of a dyke of 10-m. thickness is of more significance than the trend of a dyke of one-metre thickness. The difficulties involved make the calculation of a "weighted" average trend impractical.

Where the variation of the trend of an assemblage of dykes is such as to indicate the existence of a radial-swarm, then appropriate modification of the direction of the section for the calculations is justified. Conversely, for a swarm which is , on the whole, linear in form (fig.15), i.e. variations of the trend from the mean are of Gaussian type, adoption of a single direction of section for calculations is equally justified.

Where the average trend of the dykes diverges most widely from N.N.W., viz. in Morar and Moidart where it is N. to S., the actual densities are not exceptionally high. A value of 10 per cent. dilation, calculated using an E.N.E. to W.S.W. section, would become 11 per cent. dilation using an E. to W. section.

Refinements to the calculation of the aggregate thickness of the dykes are also possible. Two corrections considered below are those for:

(a.) the variation of the trend of each dyke, in a section, from true N.N.W.

(b.) the variation of the dip from vertical.

(a.) Consider the map of Dyke (i.), trending at an angle β to N.N.W. (fig.43a.). Point C, representing country-rock on one margin, is displaced to point B by dilation, assuming that this takes place at right-angles to the walls of the dyke. The component of this movement in an E.N.E.-direction is AB, which equals $BC.\cos\beta$, i.e. (thickness of dyke) x $\cos\beta$. Dyke (ii.), which trends E.N.E. to W.S.W. has maximum dilation in the direction N.N.W. to S.S.E., but no component of movement in the E.N.E. to W.S.W. direction.

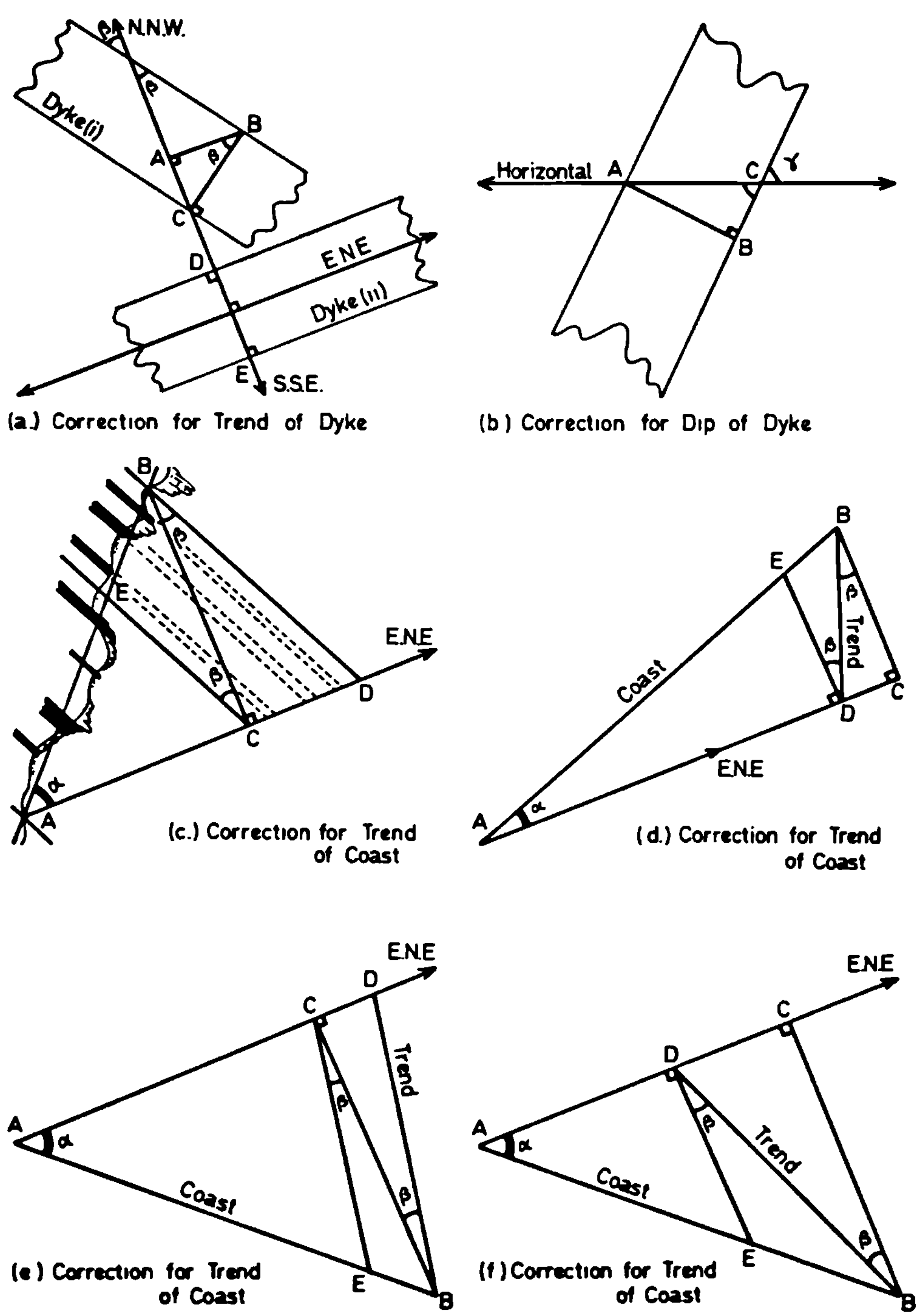


Fig.43. Possible Corrections in Calculation of Dilation

(b.) Secondly consider the vertical-section of a dyke dipping at an angle γ (fig.43b.). Point A is displaced to point C. The dilation in the horizontal is AC, which equals AB/sinγ. The corrected dilation in the horizontal-plane and in an E.N.E. to W.S.W. direction, for a dyke trending at variance to the N.N.W. by an angle β, and dipping at an angle γ, is:

(Thickness of dyke) x (cosβ) x (1/sinγ).

These corrections, apart from being tedious and laborious, assume that the strike and dip of the dykes, as seen today, are the original strike and dip, and thus bear witness to the original crustal-extension at the level which is at present exposed.

A further possible correction, and perhaps the most important of all, involves the relation between the trend of a traverse along which the dykes are recorded and the trend of those dykes themselves. Consider fig.43c., representing a coastline trending on average at an angle α to the north of E.N.E. Suppose the dykes in this section of coast trend at an angle β to the west of N.N.W. The component in the E.N.E. to W.S.W. direction, of the length of the section AB, is AC. However, on projecting the dykes to meet the line AC, it is found that three of them fall on the line CD, outside the calculated component-length of the section.

The required correction is an addition to the length of section AC (E.N.E. to W.S.W.) of CD.

$$CB = AC.\tan\alpha,$$

$$CD = CB.\tan\beta,$$

Hence, $CD = AC.\tan\alpha.\tan\beta$.

The corrected length of section is AC x $(1+ \tan\alpha.\tan\beta)$. In cases d., e., f. (fig.43), the corrected lengths of section are:-

(d.) AC x $(1- \tan\alpha.\tan\beta)$;

(e.) AC x $(1+ \tan\alpha.\tan\beta)$;

(f.) AC x $(1- \tan\alpha.\tan\beta)$.

Two difficulties arise in the use of these corrections:
(1.) For a very irregular coastline, it is difficult to determine the average trend of the section.
(2.) As demonstrated above, there is perhaps a need for a "weighted" average trend in calculating the angle β.

The most condemning criticism of the use of all possible subtle corrections has its foundations in the sometimes probable inaccuracy of observation. The omission or repetition of measurements on certain dykes is inevitable. One very short section of poor exposure, within an otherwise long and uninterrupted traverse, might easily lead to the neglect of a broad dyke, or might obscure an off-setting relationship between two outcrops of otherwise apparently separate dykes.

The conclusion to the argument of the last few paragraphs is that it is not only simpler, but also more sensible, to adopt an uncomplicated means of analysis, involving none of the above corrections.

7:IV. Selection of Lengths of Section.

Five methods of selection are discussed. These are:-

(i.) the strip method,

(ii.) the graphical method,

(iii.) the optimum length of section method,

(iv.) the sliding-kilometre method,

(v.) the method of overlapping sections.

(i.) The Strip Method.

Tyrrell (1928,p.241) divided the south and east coasts of Arran into two-mile strips, for an analysis of, among other things, the intensity of the Tertiary dykes. Tomkeieff and Marshall (1940) used a division into strips for similar analyses of the dykes of the Killough-Ardglass Swarm, northern Ireland.

The use, for instance, of strips of one-kilometre breadth trending N.N.W. to S.S.E., over the whole area of outcrop of the Skye-Swarm, is too inflexible and restricting. An individual strip may cut through sections of poor exposure, e.g. with only half the sections exposed. Such sections would be of little use for the calculation of the values of dilation for the middle points of those sections. The abandonment of a half-kilometre of exposed section, on the other hand, involves a waste of valuable data.

Moreover, one-kilometre often constitutes too long a section, where intensities of dykes are extremely high. It is impossible in such sections to determine the more detailed variations in the intensities between adjacent strips. Conversely, where intensities are low, a single-kilometre section may yield an anomalous value for the dilation, if, for instance, one dyke of 10-m. thickness is found within one strip, with no dykes present in the next two or three adjacent strips on either side.

(ii.) <u>The Graphical Method.</u>

The plot of the cumulative-thickness of the dykes, against the distance measured along the traverse computed in an E.N.E. to W.S.W. direction, for very long and continuously exposed stretches, can be informative (fig.44). Such a cumulative-thickness graph (solid line) is plotted for the dykes recorded along the coast from the Point of Sleat to Kyle Rhea. The cumulative-thickness plot is recommenced at zero-thickness at breaks in the continuity of the exposure along the traverse. The slope of the graph (dy/dx) gives the dilation at any point. The result of many calculations of this function is a plot of the values of dilation (broken line on fig.44), with extrapolations (dotted line) across breaks in exposure. Over very short distances, maximum values of dilation are very high reaching to over 40 per cent., but the most constantly high values occur over some distance and are located between abscissae 4 and 7.

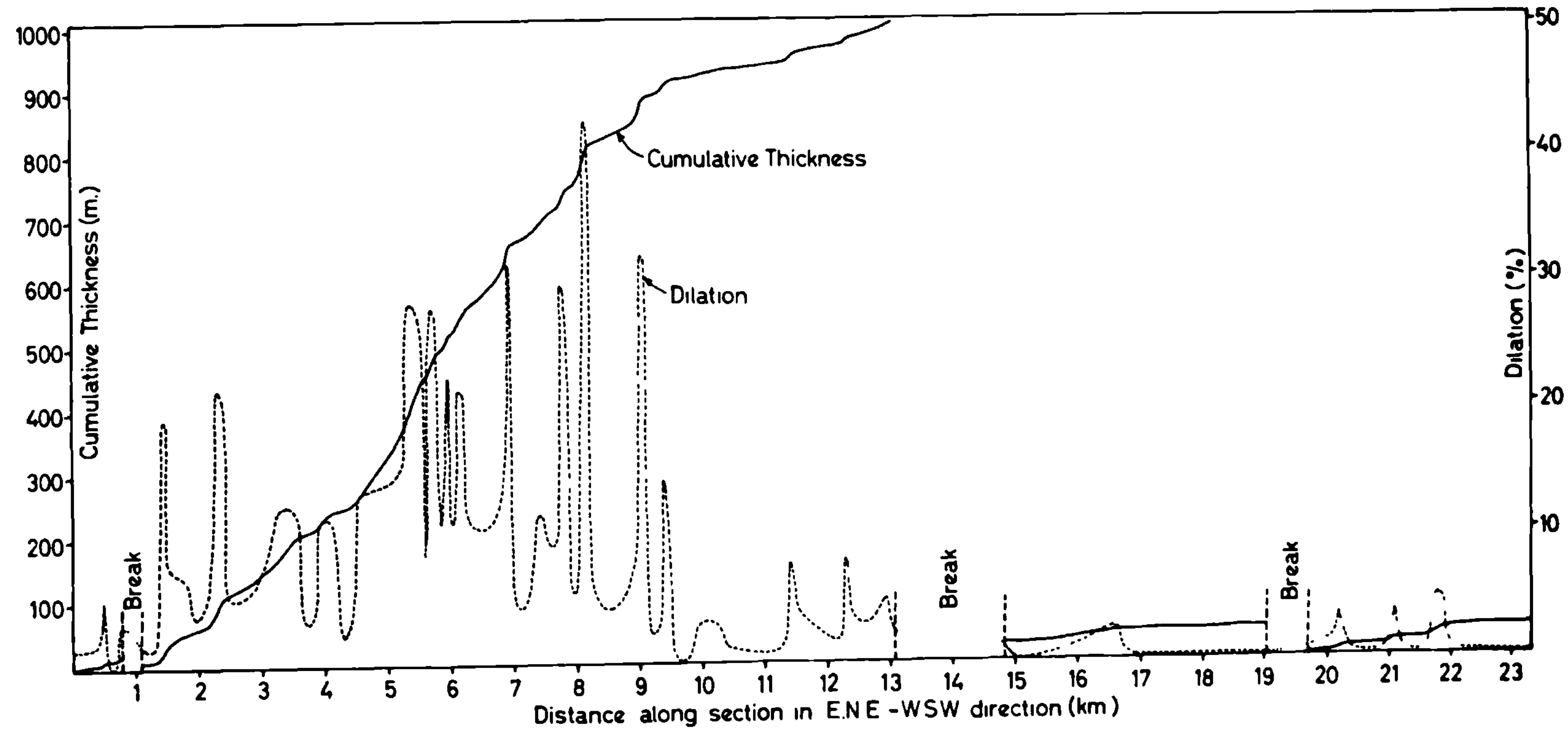
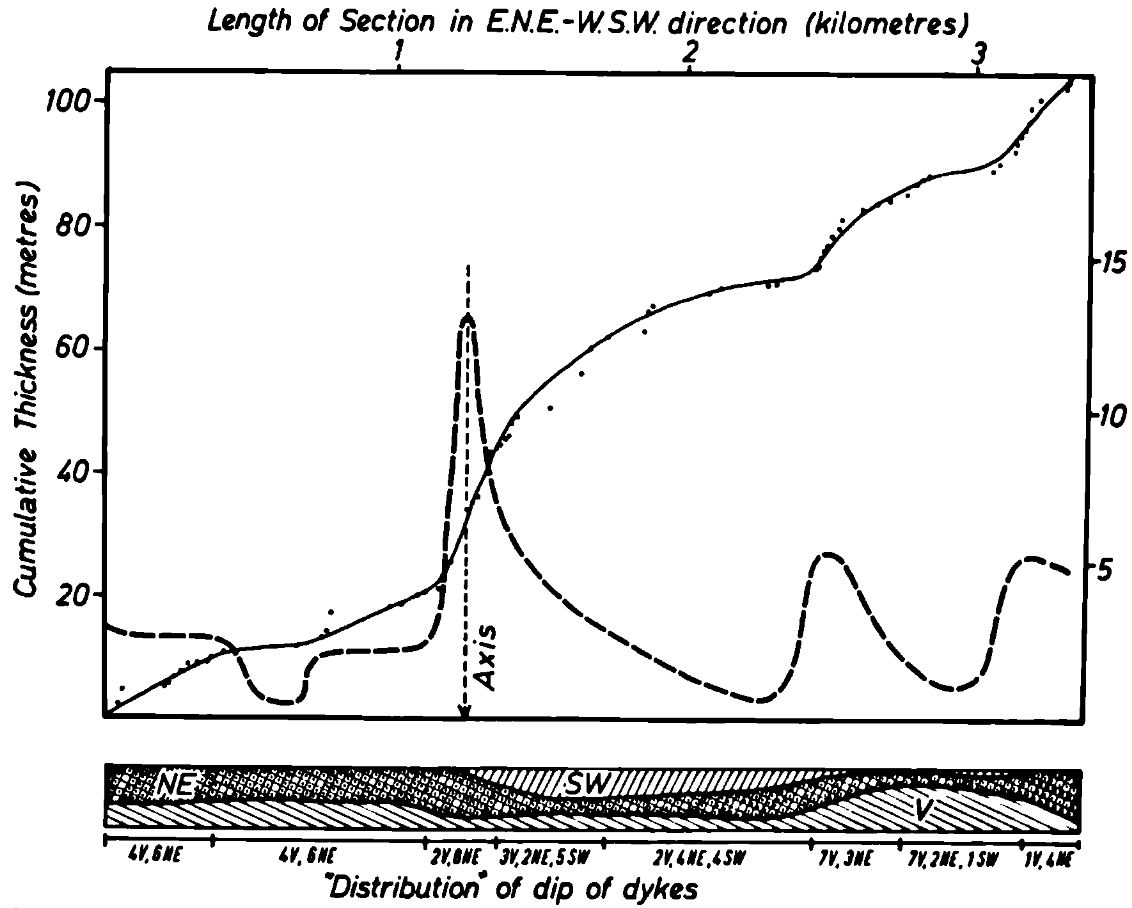


Fig.44. Cumulative Thickness Graph and derived plot of Dilation for South coast of Skye

In fig.44 the rapid variation in dilation, from repeated peak to repeated low over short distances, is an accurate representation of the intensity of the crustal-stretch. However, the contouring of such detailed variations in the dilation, from traverse to traverse across vast tracts where values are unknown, creates insuperable difficulties. The best use to which such a method can be put is in determining a reasonable position for the siting of an axis of high-intensity of dilation. In fig.44 this axial-position is not very well defined, but clearly lies between abscissae 4 and 7. Fig.45, on the other hand, illustrates a case where the axis is clear and precise. This latter figure represents an analysis of the crustal-stretch due to dykes on a section of coast trending E.N.E. to W.S.W., on the northern side of the mouth of Loch Harport (north-western Skye). In fig.45, the cumulative-thickness graph is represented by the thinner solid line, the derived graph of the dilation by the thicker broken line. (The significance of the lower part of the diagram is discussed in Chapter Ten,II).

The graphical method is a procedure by which values of the dilation can be calculated for infinitesimally short sections. The result is all too often an acquisition of unmanageably rapid variations of these values (fig.44). On the other hand, the use of long sections (say, 2km. or more) can lead to an overlooking of small and possibly significant



Analysis of Bracadale Axis at Port Beag—Dilation & Dip

Fig. 45.

changes in intensity. Since the intensity is so variable, both locally and regionally, what is required as the ideal is a sliding-scale which gives an optimum length of section for the calculation of the dilation at each locality.

(iii.) The Optimum Length of Section Method.

In one possible method, a traverse could be divided into sections the optimum length of any one of which is proportional in some way to the aggregate-thickness of dykes in the traverse. One such method, devised and tested for its applicability by the author, proved to be impractical and was abandoned. However, as an example of a type it is described below.

In this method, a traverse is divided into E.N.E. to W.S.W. component one-kilometre sections as a first stage. The aggregate-thicknesses of the dykes falling in these sections is calculated. It is then determined within which of seven standard intervals, between the values 5, 10, 20, 40, 80, 160, 200, and above 200, metres, this aggregate-thickness falls. The number 40 is then divided by the lower value of this interval to give the optimum length of section. Thus, for an aggregate-thickness of 90m. in a one-kilometre section, the best length of section for calculations of the dilation is 40/80, or one-half kilometre. The minimum length of section in this scale is one-fifth kilometre (40/200), and the maximum is 8km. (40/5). The special dividend of 40 and the standard intervals were arrived at by experiment.

In another method, the lengths of the sections may be systematically varied according to the numerical intensity of the dykes within a traverse. Such a procedure is especially advantageous where one broad dyke outcrops in a traverse containing nothing else but a few narrow dykes. Here, there is a need to increase the length of the section, thus including a large enough number of the thinner dykes to reduce the dominance of the thick dyke. An alternative argument is that the broad dyke has its own significance and should not be obscured. Such a broad dyke would be represented by a very prominent peak in a dilation-graph derived from a cumulative thickness plot. However, such a peak in the dilation leads as stated above to impracticalities.

Reduced to its limits, any sliding-scale of optimum lengths of section approaches the circumstances characteristic of the graphical method. For example, two adjacent sections in a traverse, each one-kilometre in length, may yield values of 10 and 20 per cent. dilation, respectively. There are no signs as to where the intervening one per cent. intervals lie. Four sections in the same traverse, each of one-half kilometre, may give values of 8, 12, 15 and 25 per cent. dilation, respectively. But further reduction to eight sections, each of one-quarter kilometre, may yield values of 11, 5, 9, 15, 10, 20, 30, and 20 per cent. This rapid fall and rise of the last group of values is as equally confusing as the results obtained by the graphical method. No one standard method of acquiring an optimum length of section can be employed throughout the analyses of the whole of the swarms. Conditions vary from one locality to another and standard procedures are impractical.

(iv.) The Sliding-Kilometre Method.

In this method, a standard scale, of say one-kilometre, is slid along an E.N.E. to W.S.W. line next to a traverse. The values of the dilation are marked off on the traverse, at points next to the middle of the scale, when the aggregate-thickness of dykes falling within the scale is sufficient to yield whole-number percentages of dilation. This method again involves an acquisition of rapidly varying values, with very many peaks and lows. Indeed, the principle behind this method is analogous with the graphical method.

(v.) The Method of Overlapping Sections.

If, for example, use were made of a standard one-kilometre section, twice as many values of the dilation could be obtained by overlapping at half-kilometre intervals. The principle is very much the same as that of the sliding-kilometre, although the results are not as detailed. The method is employed in this thesis in a few rare cases, where certain sections are too long for a single value, and yet too short to warrant division into two halves. Otherwise the method of overlapping sections is of little benefit.

After this detailed analysis of some possible methods, it may appear that the actual method used is illogical and unsystematic. A variable length of section is employed, but a standardization of procedure in selection of an optimum length is not used. The choice of a particular length for any section is largely determined by local factors and is in many respects an intuitive decision.

7:V. Method Adopted.

In the field, the intensity of a dyke-swarm at any locality becomes very real and tangible to the observer. In the field, it is easier for the student to grasp the significance and implications of the phenomenon of crustal-extension. Study on a day-to-day basis of the values of the dilation not only gives pointers as to what traverses — indispensable to the production of a comprehensive analysis — should be the subject of scrutiny, but also creates an intuition as to what length of section should be used for each calculation.

In these ways, belts of relatively high-intensity of dilation can be traced by mapping of appropriate traverses, and regions of low-intensity can be confirmed in like manner. The length of the section used in calculations depends upon two factors:-

(i.) the length of continuous exposure within a traverse;

(ii.) the intensity of the swarm within the traverse.

Where a traverse is very long (say, greater than 2km.), the number of divisions made of that traverse is roughly dependent upon the intensity of the dykes, in respect of both their numbers and their thicknesses. If a high value of dilation is expected for a certain length of section, then it may be necessary to subdivide it into two or more sections. Where a traverse is very short and the intensity is very low, the significance of the derived value of the dilation is very small, and such a value is used only as a guide in the drawing up of the dilation-map (fig.47, in pocket).

Fig.46 shows the relationship of the values of dilation to the corresponding lengths of section used in the derivation of such values (Appendix 9 & 9A). The distribution of the plots is roughly hyperbolic, and in this respect approaches an optimum, with short sections normally used for districts where intensities are high, and long sections for those where intensities are low.

For the dykes belonging to the regional linear-swarms the lengths of the sections are in all cases measured along an E.N.E. to W.S.W. component direction. For the dykes of the subswarms, the sections are measured along a component direction which in each case is perpendicular to the arithmetic average trend of the dykes in that section (Appendix 9B).

Argument has been levelled in criticism of this latter adjustment of the trend of the line along which the compon-

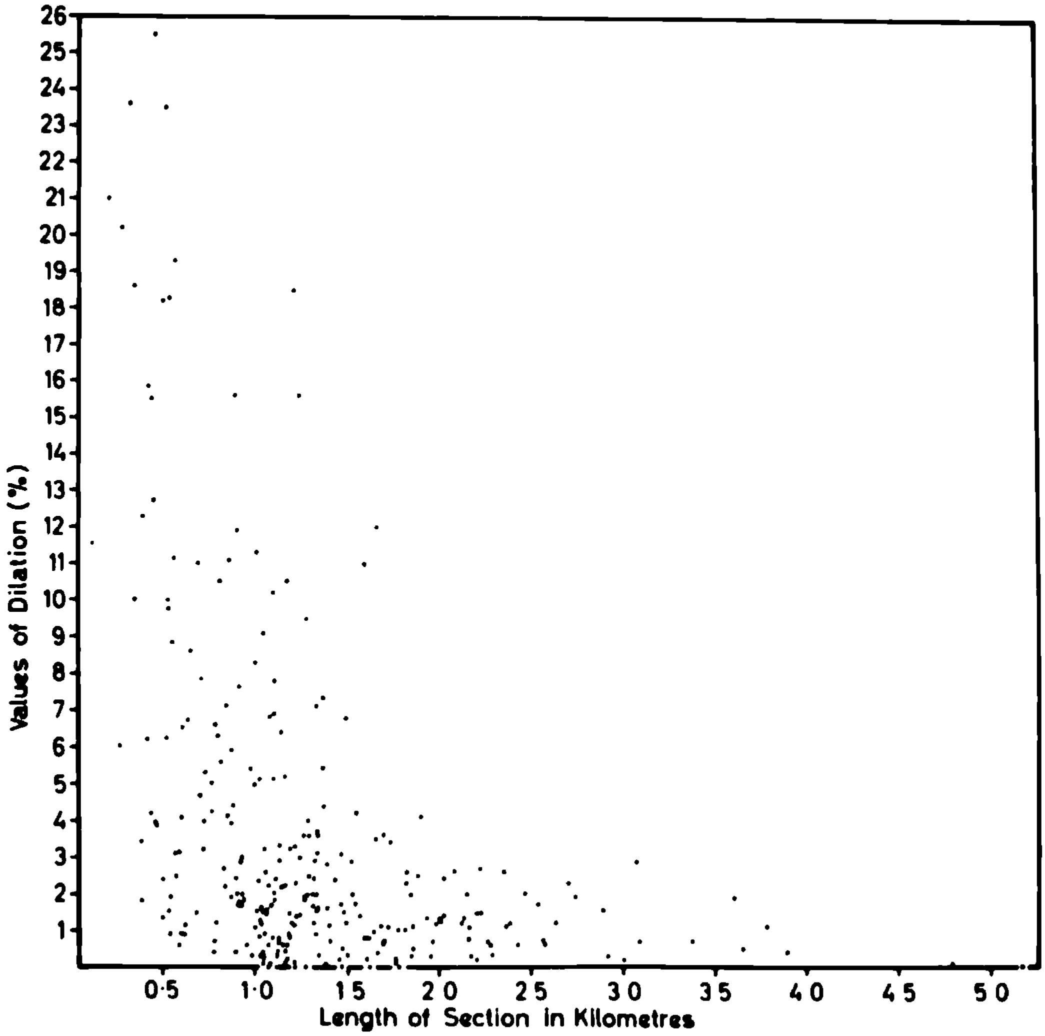


Fig.46. Plot of Values of Dilation against corresponding Length of Section

ent length of a section is measured, but with regard to the special cases of the subswarms it is considered that there is adequate justification for it. The dykes of the Broadford Bay -Applecross Subswarm are of a variety of trends. To compute an average trend for these dykes and to measure the component lengths of all sections perpendicular to this would be an illogical step. The possibility of a radial disposition of the dykes of the Glenbrittle-Subswarm was mentioned in Chapter six (IV). This possibility cannot be entirely excluded unless the method of variable-trending lines of section is used in calculations of the dilation.

In the construction of the dilation-map for the Skye and Ardnamurchan Swarms (including the subswarms), 290 sections, of total component-length 291km., and containing 5902 outcrops of dykes, are used. The total number of outcrops of dykes observed in the whole region is 6564. Some 660 of these are of little use in the production of the dilation-map, because of the poor exposure in the traverses in which they occur.

The problem of poor exposure is a restriction to an absolutely thorough analysis of the dilation. This is especially true in north-central Skye, in an inland belt extending from between Loch Harport and Portree Bay to between Loch Dunvegan and Loch Snizort. Connexion across stretches of sea, e.g. the Sound of Sleat, of contours of dilation is also attended by some difficulties.

The dilation is calculated using a summation of the thicknesses of individual dykes. Measurement of the thickness of a dyke is in most cases to the nearest 5cm. Because of the error in this measurement and because of other sources of error, values of dilation are quoted to only one place of decimals (Appendix 9), and only one per cent. intervals of dilation are plotted (fig.47, in pocket). The outer contour for the regional linear-swarm is an exception in that it is at one-half per cent. This latter is plotted to give a clearer indication of the limits of the swarms. As the intensities of the subswarms are low, one-half per cent. intervals are used to illustrate the distribution of their dykes.

The thinner lines on fig.47 are contours of the percentage-dilation associated with the N.N.W. linear-swarms. The thicker broken lines are contours of the same function for the subswarms.

7:VI. Description and Interpretation of the Dilation-Map.

Among the striking features of fig.47 is the increase in dilation towards the Central Intrusive Complex of Skye. On the north-western and south-eastern margins of the Cuillins, maximum values of 16 and 26 per cent., respectively, are observed. Unfortunately in the latter case inland exposures in northern Strathaird are too poor to facilitate extrapolation of the contours over much of this district.

The existence of generally N.N.W.-trending belts of comparatively high-intensity, i.e. relative to intervening districts on both the south-western and north-eastern borders of these belts, is another distinctive characteristic displayed by the contour-distribution. Among such belts the most outstanding, to the north of the Central Complex of Skye, are (i.) to (iii.):-

(i.) A belt trending N.N.W. from the north-western margins of the Cuillins towards Vaternish Point (N. Skye), and extending beyond to Harris.

(ii.) A belt of slightly more westerly trend, from the Cuillins, passing through the Loch Harport-Loch Bracadale district, and on towards Dunvegan Head.

(iii.) A less distinct belt of northerly-trend, passing along the eastern shores of Loch Snizort, through Uig, to Rubha Hunish.

To the south-west of the Central Complex of Skye, the percentage crustal-extension due to a minor swarm is indicated in one-half per cent. intervals. This shows that the distribution of the Glenbrittle-Subswarm of north-easterly dykes lies about a N.E. to S.W. axial region of relative high-intensity. The contours indicate that the form of the swarm is of a linear character.

To the east of the Red Hills, the dilation due to a similar minor swarm is detailed by contours. This is the

Scalpay-Subswarm of north-easterly dykes, and again its distribution is characteristic of a linear-swarm, reaching maximum dilation-values along a N.E. to S.W. axial region, in this case passing through northern Scalpay.

To the south of the Central Intrusive Complex of Skye, the most prominent belts of high-intensity are (1.) to (4.):-

(1.) A belt extending from Strathaird, through central Sleat, to meet the mainland at Arisaig. In this latter neighbourhood the belt of comparative high-intensity is divided, one branch passing through Eilean Ighe, the second about 2km. to the east. Farther south, this eastern branch again divides, one branch passing through Eilean Shona towards Loch Teacuis in Morvern, the second lying about 4km. to the east and striking southwards towards Salen.

One notable characteristic of this major belt of high-intensity and its branches is that their trend veers, from N.N.W. in Strathaird and most of Sleat, towards N. to S. on the mainland. Furthermore, all belts described heretobefore show continuous decrease of intensities away from the Central Complex, whereas this major belt and its branches exhibit small rises and falls of intensity along their lengths. Such "local highs" are located at the southern coast of Sleat, in southern Arisaig on the eastern branch, and in Moidart again on the eastern branch.

In northern Sleat the maximum dilation is below 16 per cent.: in southern Sleat it rises to above 18 per cent. In northern Arisaig the maximum is below 9 per cent.: in southern Arisaig it rises to above 10 per cent. In northern Moidart, along the line of the eastern branch, the maximum is above 4 per cent.: a few kilometres to the south it rises again to above 5 per cent. Some interpretation of "local highs" is presented later in this chapter.

(2.) A N.N.W.-trending, less intense belt than (1.) extends from near Loch Eishort, through eastern Sleat, through Knoydart, and along the eastern shores of Loch Nevis, to the district near the eastern end of Loch Morar. The north-western limit of this belt is indistinct. A N. to S. belt of low-intensities, extending over western Loch Eishort, intervenes between the major belt of high-intensity at Strathaird and this less intense belt.

(3.) An even more indistinct N.N.W.-trending belt is indicated by the curvature of the contours near the western part of Loch Morar. In the neighbourhood of Mallaig the definition of this belt fades.

(4.) The latter two belts join in the vicinity of Loch Morar to form a single belt, which extends in a N. to S. direction through Loch Eilt and Loch Shiel, towards Kingairloch. This junction creates a "local high" of one per cent. along the axial region of the belt.

In the districts to the east and south-west of the Central Intrusive Complex of Skye, further peculiarities of contour-distribution are displayed. These are described in the following four sections, (a.) to (d.).

(a.) A belt of relative high-intensity, of irregular but mostly N.N.W. trend, passes from the southern shores of Loch Hourn through to Broadford Bay and Scalpay, veering towards N. to S. through Raasay. By virtue of the intervening lower intensities, this region is largely distinct from the major N.N.W.-trending belts of high-intensity to the west, and this belt constitutes a secondary linear-swarm, which hereafter is called the Scalpay Secondary-Swarm.

(b.) A minor swarm, viz. the Broadford Bay-Applecross Subswarm, extends in a belt, with intensities up to one per cent., from Pabay, through the Crowlin Islands, to the southern shores of Loch Torridon. As mentioned in Chapter Six (IV), dykes of this swarm are also observed on the northern shores of Loch Eishort (at Rubha Suisnish). Inland exposures are, however, too poor for assured extension of the dilation-contours to the south-west beyond Pabay.

The relationship between the Broadford Bay-Applecross Subswarm and the Scalpay-Subswarm is uncertain. Consequently, the dilation-contours in the Inner Sound are illustrated with no through-connexion. The rôle of the N.E. dykes outcropping in southern Scalpay is indefinable, since they lie mid-way between the Scalpay and Broadford Bay-Applecross Subswarms

(Ch.6:IV).

(c.) A belt of relative high-intensity of dilation (in the regional linear-swarm) extends in an E.N.E. to W.S.W. direction between Pabay and Rubha Suisnish (mouth of Loch Eishort). Sections 129 and 130 (Appendix 9) were traversed in the Durness Limestone to confirm this pattern of the intensities of crustal-stretch. The belt of high-intensity coincides with the arcuate outcrop of the Jurassic and Cambrian sedimentary-rocks. It is notable, too, that within this same outcrop lies the dilation-axis of the Broadford Bay-Applecross Subswarm (Axis 9, fig.48).

In traverses along the northern shores of Loch Eishort, the rapid increase in intensity on passing from the outcrop of Torridonian, to that of Jurassic, country-rock (boundary best illustrated in fig.10) is very clear (sections 133 and 134, Appendix 9), Moreover, the high values of dilation in Broadford Bay are not entirely to be accounted for by the presence of the Scalpay Secondary-Swarm. It seems probable that the high-intensities and orientation of the contours (almost at right-angles to the main trend of the dykes) in some way reflects upon the outcrop of the Mesozoics. Geikie (1897B, vol. 2, p.124) remarked that the dykes are abundant in the Cambrian Limestone and Jurassic rocks, but that they are sparse in the Torridonian rocks, and he stated that "some formations appear to have been fissured more readily than others".

The most obvious explanation, of the distribution of the intensities of dilation in this district, is that peripheral folding (consequent upon the intrusion of the Central Complex) affected the Jurassic, and to some extent the Cambrian, sedimentary rocks, and led to the development of lines of weakness at right-angles to the fold-axes. The more competent Torridonian rocks, on the other hand, better withstood these effects, and did not form fractures in like manner. The result of this was that later dyke-injection was more intense in the weakened belt of Mesozoic rocks.

The only apparent fallacy in this latter hypothesis is that dykes intruding the Jurassic and Cambrian country-rocks in this district must have passed through Torridonian rocks before injection into the overlying younger rocks. If, as is believed, the dykes were intruded vertically from a great depth, in some way a greater aggregate thickness of dykes stems from a smaller aggregate thickness at a deeper level. It seems that at the junction between the Torridonian beds and the overlying rocks the upward-forging dykes split into a greater number of branches, following the more abundant lines of weakness in the strongly-folded Jurassic and Cambrian blocks, and that the aggregate thickness of these branches is greater than that of those dykes in the Torridonian rocks below. (The increased numbers of dykes at the Jurassic/Torridonian boundary are confirmed in the next chapter.)

(d.) To the south-west of the Cuillins, the dilation-contours display a "distortion" towards the west, in the neighbourhood of Soay. A hypothesis similar to that of the previous paragraphs is offered in explanation. In such close proximity to the intrusive "Gabbro", a distortion of the country-rock was inevitable, and such fracturing as took place led to the production of a slight increase, above the normal for the area, of numbers of planes of weakness along which dykes could later be intruded.

Throughout the above description, relationship of the observed distribution of dilation-contours to the Central Intrusive Complex of Skye has often been stressed. Three major aspects of this relationship, viz. (A.) the configuration of the dilation-contours outside and to the east and to the west of the Complex, (B.) the degree of alignment of the major belts of high-intensity to the north-west and south-east of the Cuillins, and (C.) the measurements of dilation within the Gabbro and Granite themselves, are each appropriately discussed at this stage.

(A.) It has been assumed that dykes were intruded throughout the period of extrusion of the lava-pile. In one sense, however, no corroboration of this has been derived from any observed examples of feeder-dykes. The corollary of the assumption that dyke-injection took place during the eruption of the lavas is that the number of dykes at the base of the pile is greater than at higher levels, whether there are feeder-dykes or not. If, indeed, the dykes had a source at depth, then some factor of upward decrease in intensity would be expected, no matter what the country-rock. This is an added factor to the decrease in numbers upwards through the Tertiary lavas.

In view of these facts, the idea that the dilation may be represented as a contour-map is partly unsubstantiated, since the calculations are based on the intensities of dykes in traverses occurring at different structural levels. Connexion by contours of the values of the dilation, recorded in traverses in the lava-pile and in pre-Tertiary rocks, is thus especially erroneous. The belt of relative high-intensity in Raasay (part of the Scalpay Secondary-Swarm), and the "distortion" of the dilation-contours in Soay (formerly attributed to the effects of peripheral folding and the weakening of a belt of Torridonian rocks), may in part reflect the differences which exist in the structural levels between these localities and the adjacent traverses observed in lava-terrains.

The great majority of sections studied in northern Skye are coastal, and consist either of Mesozoic country-rocks or are at levels near the base of the lava-pile. One major problem arises in the interpretation of the distribution of dykes in the stream-sections bordering the north-western margin of the Cuillin Gabbro. The projection of contours across the central region of Skye between the Cuillins and Vaternish Point, which is not only a poorly-exposed region with few recorded observations, but also a district in which the levels of the lava-pile are very variable, is perhaps the most doubtful of all projections.

One redeeming factor is that the locations of the sections of relative high-intensity, (i.) bordering the north-western margin of the Cuillin Gabbro, (ii.) at Vaternish, and (iii.) in Harris, lie on one straight line. The position of the axis of high-intensity seems to be little affected by these anomalies of observation. Nevertheless, a certain amount of latitude must be afforded to any interpretation of the intensity of dilation in the inland central region of northern Skye.

Connexion of dilation-contours, from north to south, to the east of the Central Complex is of course hampered by the outcrop of the Red Hills "Granite", but from Broadford Bay to Raasay the country-rock is of pre-Tertiary age, and the problems described above are not encountered.

(B.) The major belts of high-intensity to the north-west and south-east of the Cuillins are disposed about definite axes. These axes are not in alignment in a N.N.W. to S.S.E. direction. The possible reasons for the off-set of the belts of high-intensity are for the present (but see also Ch.16:VI,6) two-fold:-

(i.) The general veering of the trend of the belt on the south-east of the Cuillins may be more accentuated through -out northern Strathaird, and connexion with the belt to the north-west of the "Gabbro" may thus be on the same, though highly curved, line.

(ii.) The ages, for the most part, of the dykes to the north-west and south-east of the Central Intrusive Complex may be different. Consequently, the corresponding dilation-axes may trend towards two different foci within that Central Complex.

(C.) Certain calculations of the dilation are made for traverses within the outcrop of the Cuillin "Gabbro" and the Red Hills "Granite". In general such traverses were not studied because of the younger nature of the Central Intrusive Complex, in relation to the time at which intrusion of the dyke-swarms commenced. Two cases where such traverses were studied are described below.

On the north-western shores of Loch Scavaig, a value of about 4 per cent. dilation (fig.47) is obtained for about ¾km. of section in the "Gabbro" (measured E.N.E. to W.S.W.; section no.75, Appendix 9). This contrasts with a value of 10 per cent. in the section in Torridonian country-rock to the south (section no.76). An extremely approximate indication of the age of intrusion of the "Gabbro" can thus be obtained. Assuming that the rate of dyke-injection was fairly uniform, then six-tenths of the total span of time of intrusion of the dykes had elapsed before intrusion of the Gabbro, to the level exposed.

Two sections in the "Granite", each about 1¼km. in length, on the northern side of Loch Ainort, yield values of 2 per cent. dilation (sections no. 93 & 94, Appendix 9). This constant value contrasts with the westward increase of percentage-dilation in districts to the north along Loch Sligachan (fig,47). It again indicates the younger nature of the "Granite", but does not give even an approximate proportionate age. Harker (1904,p.292) remarked, on the other hand, that "the dykes in general do not cut the granite, only because they experienced a difficulty in penetrating it", and not always because the dykes predate the granite. Perhaps similar remarks may apply to the Cuillin Gabbro.

No mention, as yet, has been made of the Ardnamurchan-Swarm. Here fig.47 gives no indication of the presence of subswarms. The linear-swarm exists alone.

Belts of relatively high-intensity, of north-westerly trend, are located on both northern (east of Sanna Point) and southern (east of Kilchoan) coasts of the Peninsula, and are more or less in alignment across the Central Complex.

Decrease in intensity from these belts is more rapid towards the west than it is to the east. Certain sections near Sanna Point are in country-rocks of the Central Intrusive Complex. This undoubtedly gives rise to an acquisition of somewhat lower values of dilation than would be found in sections at the same localities in pre-Tertiary country-rock. However the position of the axial region of relative high-intensity to the east is not affected by this problem.

To the west of the main axis on the southern coast, a resurgence of intensities occurs west of Kilchoan, to above 3 per cent. dilation. This marks the position of a secondary -swarm. In north-eastern Mull a similar belt of local high-intensity (Sloan,1970,p.40) is found. These latter dykes probably belong to the same secondary-swarm.

The contours in the neighbourhood of Ardnamurchan have been terminated abruptly by the author (fig.47). To the south and west of these terminations is the realm of what can be broadly described as the Mull-Swarm. Sloan (1970,p.43) has data which demonstrates that the belt of relative high-intensity east of Kilchoan passes into Morvern, but that farther to the south-east the definition of this belt becomes poor and it is obscured by the Mull to Morvern connexions (see below). The secondary-swarm to the west of Kilchoan also fades into obscurity to the south as it encroaches upon the main regional linear-swarm of Mull (Sloan,1970,p.40).

The line at which the dilation-contours are ended near Loch Teacuis (fig.47) marks the position where intensities of crustal-stretch are at a minimum for the district. In other words, the intensities increase away from this line towards Skye to the north and towards Mull to the south. Sloan (1970,p.43) has the data which shows that a swarm of dykes, of trend varying between N.N.E. and N. to S., passes north of Loch Aline and decreases in its intensity away from the Central Intrusive Complex of Mull towards Morvern.

Some other noteworthy points concerning the limits of the swarms are aptly discussed at this juncture. The linear-swarm in Skye, for instance, occupies a much broader region in the districts to the north of the Central Complex than in the districts to the south; and this is irrespective of an even greater spread if the distribution of the subswarms is taken into account.

In other respects volcanic activity to the north of the Central Complex of Skye is likewise of much greater development. Outcrops of the extensive lava-pile cover much of northern Skye, and remnants of it are scarce to the south. This could possibly be due to a tilting of the area towards the north followed by differential erosion. For the present, it can only be assumed that where the extrusive activity is seen to be of most widespread nature, there the intensity of the dyke-swarm is conformable in that it likewise occupies a broad region.

Towards the southern limits of the Area of Study, the Skye-Swarm is illustrated as ending abruptly at the line of the Great Glen Fault. Observations along sections in Lismore and the southern shores of Loch Linnhe at Benderloch and to the north-east in Appin, reveal the sparsity of Tertiary dykes in this area (sections no. 254 to 258, Appendix 9). This is in direct contrast to the numbers of dykes recorded on the opposite shores of Loch Linnhe (sections no. 242 to 253). The conclusion is that the line of the Great Glen Fault acted as a barrier to the continued southerly extension of the linear-swarm.

Holgate (1969,pp.109-15) proposed that a dextral wrench of 18 miles, consisting of a 5-mile displacement on the Great Glen Fault and a 13-mile displacement on the Firth of Lorne Fault, took place after the emplacement of most, if not all, of the Tertiary dyke-swarms. As a result, the dykes of the Oban district were considered to be extensions of the Skye-Swarm in Kingairloch, and the dykes of Croggan (south-eastern Mull) were brought into line with those of Jura. The differences in the intensities of the dykes, between Kingairloch and Oban, and between Croggan and Jura, refute this hypothesis. It appears, too, that Holgate took many of the dykes on the north-western shores of Loch Linnhe and on Lismore to be of

Tertiary age, whereas the present author is of the opinion that most of them are members of a Permo-Carboniferous suite (Appendix 26). A dextral displacement of about 7km., later than the Permo-Carboniferous dyke-swarm but earlier than the Tertiary dyke-swarm, is indicated by the distribution of these swarms (Appendix 26).

The limit of the Ardnamurchan-Swarm on the east of the Peninsula is of especial interest. East and south-east of Ockle Point is a region of very low-intensity of dilation (less than one, and in parts less than one-half, per cent. dilation). The axial line of this corridor of low intensities is taken as the dividing-line between outcrops of dykes belonging to the Skye-Swarm and the Ardnamurchan-Swarm.

Such a distinct division cannot be made between the Ardnamurchan-Swarm and Mull-Swarm, nor between the latter and the Skye-Swarm. South-west beyond Loch Teacuis, intensities of the dykes begin to increase towards Mull. The division between the Skye and Mull Swarms can thus arbitrarily be drawn at the termination of the ornament on fig.47. The outcrops of dykes observed in the Area of Study, except for those to the west of the Ardnamurchan/Skye Swarms dividing-line (and in the Small Isles) can thus be generally referred to as outcrops of members of the Skye-Swarm.

The outcrops of dykes observed to the west of this same dividing-line, in the Ardnamurchan Peninsula, are referred to as members of the Ardnamurchan-Swarm, although other members of this swarm outcrop in Morvern and Mull (see above), and possibly in the Small Isles (Ch,11:I & II).

7:VII. Axes of Dilation.

Fig.48 is derived from the contoured dilation-map, and shows the major axes of high-intensity of crustal-extension for regional linear-swarms and subswarms within the Area of Study. For the sake of simplicity, the axes of dilation of dykes on the Small Isles are also shown, although no further comment is made on these at this stage. The thickness of the line representing each axis is proportional along its length to the value of the dilation at all points along the middle of this line. This function is in most respects proportional also to the clarity of the axis. Broken lines represent extrapolations of axes over considerable distances of poor exposure; alternatively they signify poor definition of the axes. The curving axis through Soay (not lettered on fig.48) represents the "distortion" of the contours of dilation at this locality. Projection of axes '2C','6B', and '6C', through Morvern and to Mull is on the basis of Sloan's (1970, pp.39-43) work: the latter two axes pass farther southwards than is indicated.

Away from the Central Intrusive Complexes, axes show marked bifurcations. South of Arisaig, the branching of the axes may perhaps be related in some way to the rapid decrease

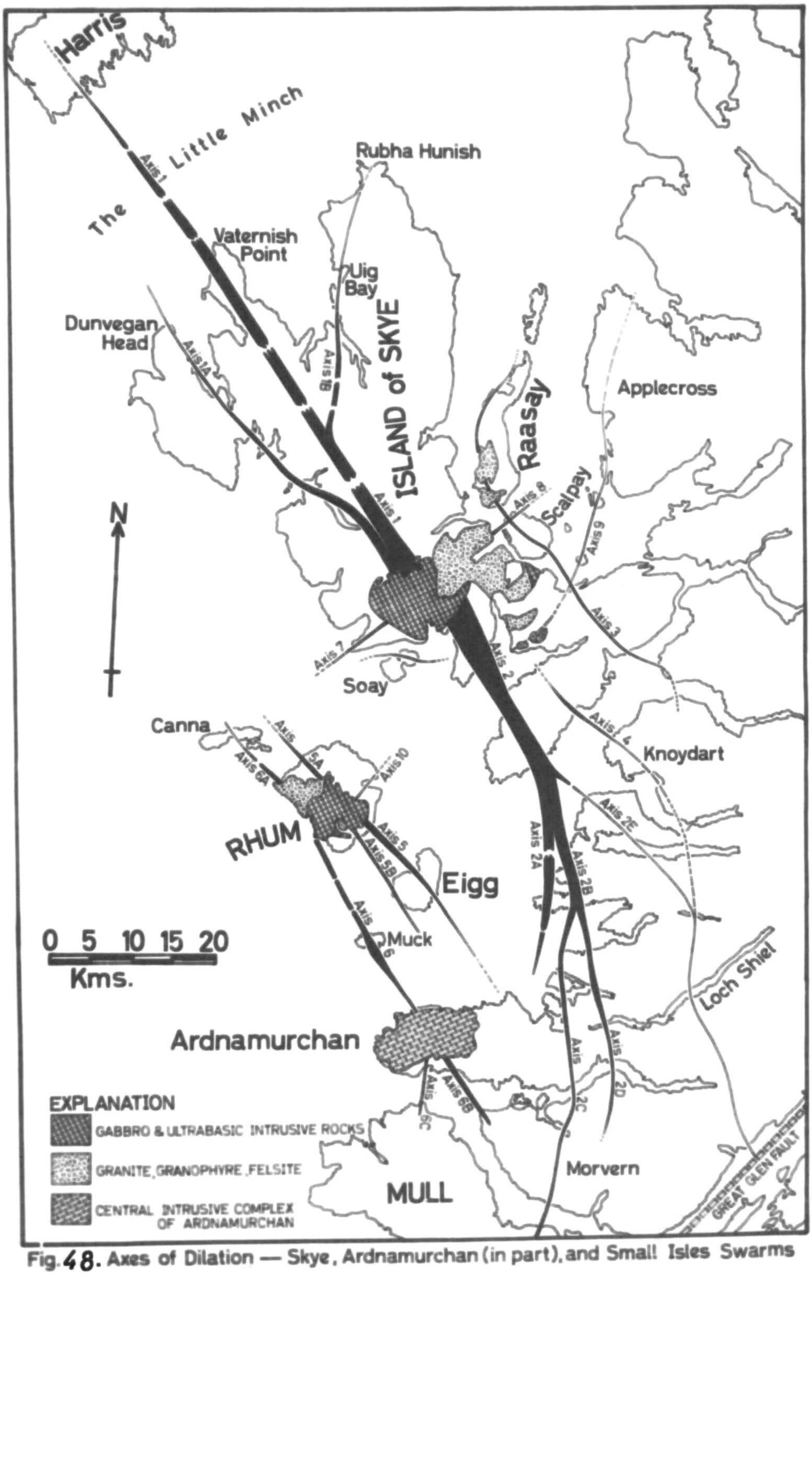


Fig. 48. Axes of Dilation — Skye, Ardnamurchan (in part), and Small Isles Swarms

of dilation from here southwards to Moidart (fig.47). Fig.37 illustrates a fold within the Moine Series in the Ardnish Peninsula (at the east of the Sound of Arisaig). In Ardnish the dykes are very sparse. To the east of Ardnish, where the strike of the foliation of the Moine is north-easterly, intensities are low again. The orientation of this foliation has some effect on the intensities as well as the trends (Ch.6:VI) of the dykes. It is possible that the structure of the Moinian in the Sound of Arisaig is a continuation of that in Ardnish, and that this is partly responsible for the decrease in intensities across the Sound from north to south.

A further point of interest is that axes '7' and '8' lie on the same straight line, and that this line is exactly at right-angles to axis '1'. Axis '1' itself is of straight line course from the borders of the Central Intrusive Complex, through Vaternish, to Harris. Axis '2', on the other hand, curves to become of N. to S. trend in Morar and Moidart, where its direction reflects the trend of the dykes in the region.

The trends of the dykes, outcropping in the belts of high-intensity about many other axes, have this same tendency to mirror the direction of their associated axes. For example, the "fanning" of the trend in northern Skye is similar in form to the "fanning" of the axes '1A','1', and '1B'. The swing of the trend from N. to S. to N.N.E. to S.S.W. of axis '2C' reflects a similar change of trend of the dykes in Morvern.

The relationship of the trends of the dykes in the Broadford Bay-Applecross Subswarm to the trend of the axis of dilation is again largely of concordant character. In many respects, this axis is very similar to the Mull-Morvern axis ('2C'), which connects to the Skye-Swarm. Where the Arran-Swarm "merges" into the Mull-Swarm, in Bute, the same swing of trend is observed (fig.1), and it is highly probable that a similar change in the direction of a corresponding axial region is to be found. If the analogy is taken to its ultimate limits, then the dykes in Applecross are members of some swarm extending southwards from a "centre" in the vicinity of the Island of Lewis. Further comment on this topic is made in later chapters (12:II;13:V).

7:VIII. Age of the Subswarms.

Because of the almost total restriction to the observation of well-exposed sections, the number of recordings of the age-relationships of dykes of very different trends is few. Undoubtedly this number could be increased by tracing some dykes inland to the points where they intersect, although exposures at no great distance from the shore often prove to be inadequate for this purpose.

Fig.49 illustrates an analysis of the cutting-relationships of dykes of various trends in southern Skye. Three of the four arbitrarily demarcated regions are of prime concern,

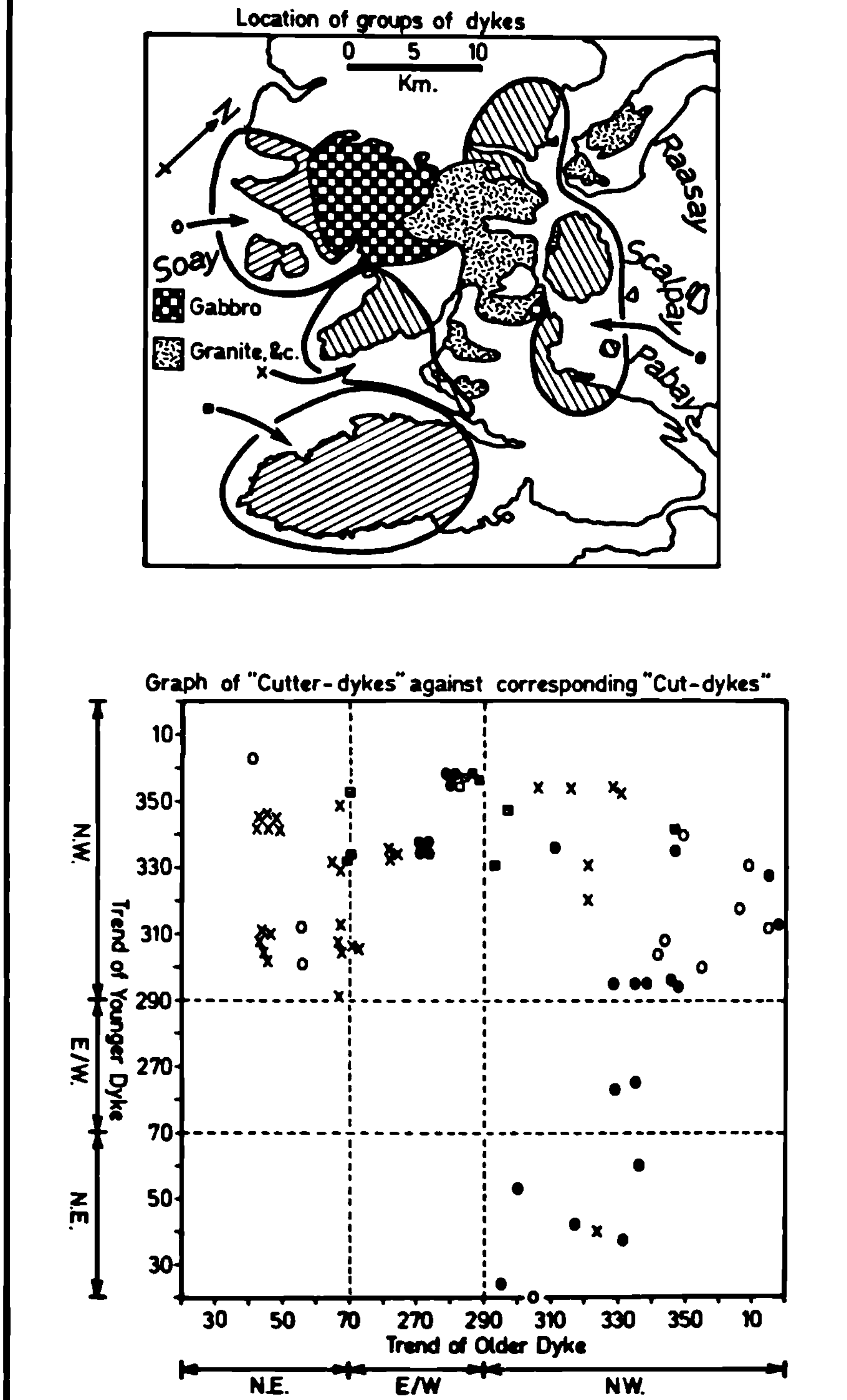


Fig. 49. Cutting-Relationships for dykes in Southern Skye

whereas the fourth region (Sleat) and the age-relationships of the N.W. dykes to each other are of little relevance to the present discussion. (The intervals for 'N.W.', 'N.E.', and 'E. to W.' trends, in this present discussion, are indicated on fig.49.)

In the region to the south-west of the Cuillins, three dykes of N.W. trend are seen to cut N.E. dykes, and only one example of the reverse relationship is observed (fig.49). In the Loch Sligachan-Scalpay-Broadford Bay area, seven N.W. dykes cut E. to W. dykes, and there are two examples of the opposite relationship. In the same area, five N.E. dykes cut N.W. dykes. In the Strathaird-Rubha Suisnish area, the relationship between N.W. and N.E. dykes is reversed, and nearly twenty N.W. dykes cut N.E. dykes.

Now, the E. to W. dykes of the Broadford Bay area and the N.E. dykes of the Rubha Suisnish area are both cut by N.W. dykes. These E. to W. and N.E. dykes are mostly members of the Broadford Bay-Applecross Subswarm, and the evidence points to the conclusion that the Subswarm is older than most of the dykes of the Scalpay Secondary-Swarm.

Evidence on the N.E. dykes of the Glenbrittle-Subswarm also indicates a proportionately older date than that of the intrusion of the N.W. dykes of the area. The converse, however, is true for the N.E. dykes of the Scalpay district. These latter dykes are members of the Scalpay-Subswarm.

The number of recordings in all cases is, nevertheless, too small for absolutely certain deductions. The relative age of the main linear N.N.W. swarm and the Scalpay Secondary-Swarm is, of course, not known. Consequently, the fact that the N.E. dykes of Glenbrittle and Scalpay have a different age-relation to the N.W. dykes cannot be taken as proof of their distinction. Indeed, the alignment of their axes of dilation suggests very strongly a contemporaneous nature, and this, in turn, would bear the corollary that the Scalpay Secondary-Swarm is relatively older than the main linear-swarm.

7:IX. Volume of the Dykes.

Fig.50 includes a diagrammatic representation of the surface-area of the dykes of the N.N.W. linear-swarm at the present level of erosion. This embraces the entire region covered by the Skye Dyke-Swarm, with boundaries as described above. Secondary-swarms are included, although subswarms are not. No attempt is made to illustrate the asymmetry of the distribution of the swarm due to the existence of these secondary-swarms.

The graph is constructed from calculations of the aggregate thickness of dykes in sixteen serial E.N.E. to W.S.W. sections, which are separated by intervals of 10km. (except sections '1A' and '2A', which are 16km. apart) in a N.N.W. to S.S.E. direction. The values of the aggregate thickness

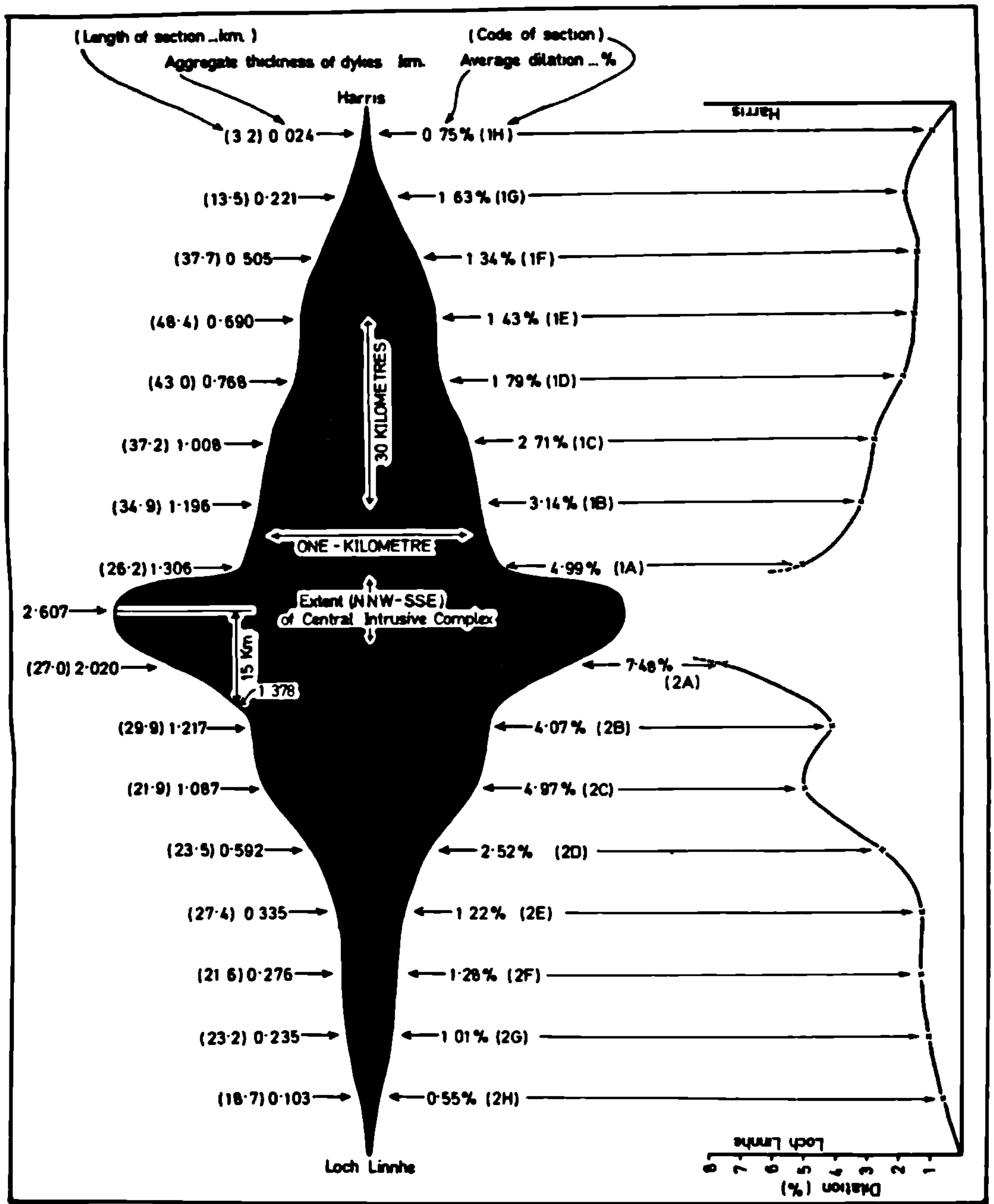


Fig 50. SURFACE-AREA of OUTCROPS of DYKES in SKYE-SWARM. DILATION across TOTAL BREADTH of SWARM.

of the dykes in, the length of, and the average dilation in, each of the sections are derived from fig.47. The extent of each section is taken between the one-half per cent. contours on either margin of the swarm. The procedure is then a simple one involving computation and summation of the hypothetical thickness of the dykes between successive contours.

By plotting these values of aggregate thickness on a graph, an approximate evaluation of the total surface-area of the outcrop (if all dykes are assumed to be vertical) can be obtained. Extrapolation between sections '1A' and '2A' is based on three assumptions: (i.) that the increase in aggregate thickness between sections '2B' and '2A' is fairly well sustained, (ii.) that dykes to fit this distribution existed in the region before the intrusion of the Central Complex obliterated most of them, and (iii.) that the maximum aggregate thickness occurs in an E.N.E. to W.S.W. section passing through the middle of the N.N.W. to S.S.E. extent of the Cuillin Gabbro (indicated on fig.50 as the "extent of the Central Intrusive Complex").

The surface-areas of the dykes to the N.N.W. and S.S.E. of the Central Complex are very much the same. As stated earlier, the lateral extent of the linear-swarm on the northern side of the Cuillins is greater than it is to the south, and also maximum values of dilation are lower to the north. Yet, when the aggregate thicknesses across the entire breadth of the swarm are considered, there is little difference to north and south, except for the high values in section '2A' (fig.50). This latter, however, is in some measure off-set by the more rapid decrease in aggregate thicknesses to the south than to the north of the Central Complex.

The total surface-area at the present level of erosion, calculated from fig.50, is 128km^2. The maximal limits of error for this value are perhaps about 10 per cent. The area occupied by the Skye Dyke-Swarm (within the one-half per cent. dilation-contour) is about 4150km^2. The dykes occupy 3.1 per cent. of this total area, at the present level of erosion. Extrapolation between sections '1A' and '2A' gives a value of 2.607km. for the maximum aggregate-thickness along the E.N.E. to W.S.W. section passing through the middle of the outcrop of the Gabbro.

In the Hebrides, suitable exposures, of an extent considerable enough for the determination of the rate of decrease in the intensity of the dykes vertically upwards, are lacking. A knowledge of both this rate and the overall height of a dyke-swarm would aid in the determination of the total volume of dyke-material. Such a determination is desirable since the purpose of it is to obtain some expression of the great significance of the swarms, especially in the light of comparison of the volume of dyke-material with that of the lavas or that of the basic plutonic bodies of the Central

Complexes.

G.P.L. Walker (1960) gave graphical illustrations of the vertical fall-off of the percentage crustal-stretch and number of dykes per mile for eight belts in the Tertiary basalts of eastern Iceland. However, Walker's calculations were based on the premise that this decrease, vertically upwards in the lava-pile, is due to the fact that all of the dykes are feeders, and as such those rates give no indication of the behaviour of the dyke-intensities in the Hebridean swarms in the pre-Tertiary basement.

Because of the difficulties involved, only very approximate indications of the possible values of the total volume of the dykes, e.g. in the Skye-Swarm, can be offered. As an initial assumption, consider that the dyke-swarms extend to a depth of 15km. (depth of the Intermediate layer of seismology) below the present level of erosion to meet, as also probably do the basic plutonic bodies of the Central Complexes (McQuillin & Tuson,1963), some horizontal magmatic layer. In the case of the Skye-Swarm, the surface-area of the dykes ($128km^2$.) at the present level is about 3.1 per cent. of the total area (ca.$4150km^2$.) occupied by the swarm. If the surface-area of the dykes increases in a linear manner to become 100 per cent. at 15km. depth, then the surface-area of the swarm is zero at about one-half kilometre (3.1 x 15 / 96.9) above the present level. The overall height of the swarm is thus $15\frac{1}{2}$km. The average surface-area of the dykes is 4150/2 km^2. The volume of the dykes is, therefore, about 32,000 km^3. This value seems to be unrealistically large, and, indeed, it can be taken as an absolute maximum.

If there is no increase in intensity with depth, and without taking into account the volume of dyke-material removed by erosion (which must be small in comparison with that amount extending to depth), then a minimum value of the volume of the dykes in the Skye-Swarm, from the present level to a depth of 15km., is about $1900km^3$ (15 x 128).

A third possible method of determination of the volume of dyke-material involves the unlikely assumption, that the rate of change on the horizontal of the aggregate-thickness of the dykes across the swarm is paralleled by a corresponding behaviour of the dykes in depth. This assumption is based on the unsubstantiated analogy drawn between the rate of decrease in the horizontal away from the middle of the Cuillin Gabbro, and the rate of decrease in the vertical away from a postulated horizontal magma-layer, from which not only the dykes but also the basic material forming the Cuillin basic pluton arose (McQuillin & Tuson,1963).

The aggregate thickness of the dykes decreases by a factor of one-half, from 2.607 to 1.378 (fig.50), over 15km. on the horizontal to the south of the Central Complex. Hence, by the analogy described, the surface-area of the dykes at

15km. depth is 256km^2 (2 x 128). At the middle-depth of the swarm, this surface-area is an average of 192km^2 Hence, the total volume calculated on this basis, again without taking into account the amount removed by erosion, is about 2900km^3 (192 x 15).

The surface-area of the outcrop of the Cuillin Gabbro is about 72km^2 Taking into account the basaltic material which lies beneath the Red Hills (McQuillin & Tuson, 1963), the surface area of the pluton, but for this partial cover by granitic rocks, would be about 240km^2 The surface-area of the dyke-swarm is of an equally impressive magnitude. The volume of the dyke-material, too, though the calculations are highly speculative, is sufficient to warrant the application of the term "major igneous body" to the dyke-swarm.

On the assumption that the lava-pile of Skye has the three-dimensional form of the cap of a sphere, i.e. a plano-convex body, and has a diameter of 50km. and maximum thickness of 2km., then its total volume is less than 2,000km^3 Assuming that the basic pluton beneath the Central Complex of Skye is cylindrical in form, and of maximum diameter, 18km., and depth, 15km., then its volume is less than 4,000 km^3 The Skye Dyke-Swarm is entirely comparable in its dimensions with the major igneous bodies of the lava-pile and basic pluton.

Though a major body, the regional linear dyke-swarm of

Skye averages at present level at less than 1km. in breadth, since it extends a distance of over 150km. N.N.W. to S.S.E. The pre-Tertiary geology of the area is displaced by the emplacement of the swarm by no more than either an average of 1km., or a maximum of about $2\frac{1}{2}$km., in an E.N.E. to W.S.W. direction. Most of the pre-Tertiary geological-boundaries lie parallel to this direction, e.g. the Moine Thrust in Sleat. After due consideration, it seems that a restoration of the geology of the Area of Study to its pre-Tertiary configuration would be an analytical exercise of little profit, and such is not attempted here.

7:X. "Local Highs" of Dilation.

Certain aspects of fig.50 provide partial explanations of the occurrence of "local highs" of dilation. In sections '2B' and '2C', the aggregate-thicknesses of the dykes decrease from 1.217 to 1.087 km. The average dilation, on the other hand, increases from 4.07 to 4.97 per cent. (see also the graph of the values of average dilation, on the right of fig.50). This is because the breadth of the swarm is disproportionately narrow in section '2C'. In such sections as '2C' "local highs" of dilation are to be expected, in order to off-set the pinching of the breadth of the swarm.

Reference to figs. 47 and 48 shows that certain "local highs" are located where the axes of dilation bifurcate. In the particular case of the "high" in Moidart, along axis '2D', this local anomaly is possibly due to the fact that the complexity of the Moine Series in the Sound of Arisaig leads to an abnormal "local low", and that where the strike of the foliation is of regular N. to S. orientation, farther to the south, the normal intensity reasserts itself (fig.37). The high of one per cent. in the Crowlin Islands (fig.47), on the Broadford Bay-Applecross Subswarm, may, on the other hand, possibly be due to the inclusion among the recorded outcrops on Crowlin of members of the Scalpay-Subswarm.

7:XI. Dilation and Time.

In conclusion, to put the results of the analyses described in this chapter into perspective, some comments must be made on the factor of time.

The dykes of the linear-swarms may have been intruded either at a uniform rate or spasmodically, but in either case throughout some period of time. The cross-cutting relationships between dykes of the linear-swarms throughout the Area of Study (e.g. the "N.W. dykes" of Central Skye shown on fig. 49), as well as the chilling of dykes one against another in many multiple-intrusions, are adequate attestations to the reality of this time-span.

To reach a fuller understanding of the fundamental tectonic significance of the linear-swarms, and indeed the subswarms too, a perception of their evolution through time is required. If the age of each dyke could be determined accurately by radiometric methods, then the opportunity to plot the dilation for different intervals or spasms would present itself.

In the absence of isotopic-dates on the dykes, one conceivable alternative is to suppose that the factors controlling the intrusion of the dykes changed systematically with time, in such a way that the trends of the dykes altered progressively with age from, say, a preponderance of N.W. dykes to one of N. to S. dykes. Then contour-maps showing the crustal-extension due to dykes falling within certain intervals of trend would indicate this time-sequence. However, the influence of factors which would remain independent of such a postulated time-sequence, e.g. the control of the foliation of the Moine rocks (Ch.6:VI), and that control which an older dyke exerts on a younger dyke in a multiple-intrusion (Ch.8: II; 15:III,b), hinders the interpretation of such maps.

The geographical distribution of the trends of the dykes (Ch.6) indicates, in fact, that an assemblage of dykes at any one point along any axis of dilation is of a variety of trends. This does not appear to have made the axes any the less distinct. If, indeed, the trends of the dykes did vary with time, then it is evident that this had little effect on the locations of the major axes of dilation of the linear-swarm.

The subswarms may, of course, be exceptional in that the locations of their axes could be dependent upon some factor which may have been operative at specific times, and not throughout the whole period of dyke-intrusion within the Area of Study. This opinion, however, is modified in later chapters (Ch.16:III & IV).

Chapter Eight

THE NUMBERS OF THE DYKES

(including AN ACCOUNT OF THE MULTIPLE-DYKES)

8:I. Numbers of Dykes.

A contour-map of the intensity of the crustal-stretch (fig.47) is one means of illustrating the form of the dyke-swarms. Another simpler, though perhaps less informative, analysis is that of the intensity of the dykes by their numbers. Despite its relative simplicity, a contour-map of the number of dykes per kilometre (fig,51,in pocket) yields valuable additional evidence on the distribution of the dykes.

Fig.51 is constructed on the same foundations (Appendices 9, 9A, 9B) as the dilation-map (fig.47), and the same problems (Ch.7:IV & V) are encountered. The major points of interest stemming from a study of fig.51 are discussed below. ("Dykes per kilometre" is henceforth abbreviated to "d.p.k.")

The intensities of numbers of dykes show increases towards the Central Intrusive Complex of Skye, and more especially towards its north-western and south-eastern margins. The belts of high-intensity by numbers largely coincide in position with the belts of high values of dilation (fig.47), both in the regional linear-swarms of Skye and Ardnamurchan and in the subswarms of Skye (subswarms represented at intervals of 5 d.p.k. by thick contour-lines). A further similarity to the dilation-map is the separation shown by a "band" of low intensities (below 2 d.p.k.) of the Ardnamurchan-Swarm from the Skye-Swarm.

In certain aspects, figs.47 and 51 are dissimilar. Local highs, e.g. in an axial position (fig.48) on southern Sleat, are present on fig.47 but absent from fig.51. It may justifiably be commented that the choice of the unequal contour-interval, used on fig.51, could obscure the existence of these phenomena. However, comparison of sections 139 to 142, with section 155 and its surrounding sections (Appendix 9), indicates that a local high of number of dykes is not present on southern Sleat.

The dykes in Kingairloch are of an intensity ranging between 10 and 20 d.p.k. Such intensities are not met again in a traverse from Kingairloch towards N.N.W., through Loch Shiel, Loch Morar, to Knoydart and Skye, until northern Sleat is reached. This local high of number of dykes in Kingairloch is more sharply defined than that exhibited by the behaviour of values of dilation along this same traverse.

One further item of difference is that the position, in Harris, of the axis of the number of dykes is slightly displaced to the south-west of that position indicated by the dilation-contours.

Plotting as contours the lowest values of 1, 2, and sometimes 5, d.p.k. is very difficult, especially where projections are made over long distances where exposures are absent. Even the eastern boundary-contour of 1 d.p.k., which is mostly located on land, is of very approximate position. Higher values are much more accurately sited.

Values of number per kilometre above 100 are plotted at intervals of 50 d.p.k., and are shown without ornamentation on fig.51. To the north of the Central Complex of Skye, maximum values range above 100, but are less than 150, d.p.k. To the south of the Cuillins, the intensities range much higher, viz. to over 250 d.p.k. MacCulloch (1819,p.396) remarked upon the great numbers of dykes in Strathaird, and gave figures of 6 or 8 dykes in 50 yards of traverse. The maximum intensities recorded by the present author are (Appendix 9):-

(i.) N.W. of the Central Complex of Skye: 134 d.p.k. (section no.86);

(ii.) S.E. of the Central Complex of Skye: 299 d.p.k. (section no.114).

To the north-west and south-east of the Central Intrusive Complex of Ardnamurchan, intensities are very much lower than in corresponding locations in Skye. The maxima (Appendix 9A) are:-

(i.) N.W. of the Central Complex: 30 d.p.k. (section no.5);

(ii.) S.E. of the Central Complex: 28 d.p.k. (section no.16).

Despite the high intensities of numbers to the south-east of and near the Central Complex of Skye, the decrease towards Sleat is extremely rapid. The 60 d.p.k. contour-line, for example, does not reach the southern coast of Sleat, whereas it does reach far to the north-west. This contrasts with the plot of the dilation (fig.47), where, for example, the 8 per cent contour extends as far from the Central Intrusive Complex of Skye in either N.W. or S.E. directions. In addition, the 12 per cent dilation-contour reaches 30km. from the southern margin of the Cuillins to the Sound of Sleat, but terminates well to the south-east of the coast of Vaternish at 16km. from the northern margin of the Cuillins.

These differences, between the lateral extent of the contours of dilation and of number, are evidently closely dependent upon some variation in the thickness of individual dykes. This variation is analysed later (Ch.9;II).

Such differences, between the rate of decrease by number and by dilation, stand in contrast to certain other cases where similarity between the patterns of distribution on figs.47 and 51 is very clear. These resemblances are:-

(i.) The low numbers of dykes to the south-east of the Great Glen Fault are similar to the low values of dilation in that district (sections 254 to 258, Appendix 9).

(ii.) There is a rapid decrease of numbers, on passing from the Jurassic to the Torridonian country-rocks on the northern shores of Loch Eishort — comparable with a similar decrease in dilation in that locality.

(iii.) There is a rapid decrease in numbers, and a corresponding decrease in percentage crustal-stretch to the south of the Sound of Arisaig.

(iv.) The connexion to the Mull-Swarm, which is not indicated on fig.51, is of a similar character to that described in the previous chapter. That is to say, intensities by numbers decrease through Moidart and Sunart to a minimum in northern Morvern, and progressively increase again southwards from this last district to the Central Complex of Mull (Sloan, 1970,pp.40-5).

In summary, the configuration of the main and secondary linear-swarms and the subswarms, and the positions of their axes with their bifurcations and veering trends (especially in Morar), are, with a few exceptions, of very much the same form whether analysis is on the basis of dilation or number.

8:II. Multiple-Dykes of the Regional Linear-Swarms.

While dealing with the numbers of the dykes, it is convenient to discuss the closely allied topics of the distribution of multiple-dykes and the phenomenon of "grouping" of dykes.

Harker (1904,p.238,fig.52) gave an approximate indication of the distribution in Skye of the multiple basic dykes. He pointed out that they are mostly found in an elliptical area, extending from north-central Skye (east of the mouth of Loch Harport) to the middle part of the northern coast of Sleat. The area bulges towards the north-east and south-west near to the Central Complex, to include the heads of Loch Eynort and Loch Sligachan, most of Strathaird, and districts to the west of the Cuillins including eastern Soay.

A more detailed indication of the distribution of the multiple-dykes of the N.N.W. linear-swarm is shown as fig.52 (in this account). This contour-map is constructed by allocation of the value of the percentage-number of dykes, which are involved in multiple-intrusions, in each of the 74 groups to its respective centre-spot, with subsequent contouring. Appendix 10 (right-hand column) gives a list of these values. A notable point is that, because of an excess (over the 100 for a group) of about 30 dykes in the Greshornish area, values of 10 and 19 per cent. are given for two groups of 100 (with about 70 dykes common to each). One group is made up by using data on dykes on the north-western (codes of outcrops: 'LD'), and the other by using data on dykes on the south-eastern (codes of outcrops: 'GR'), coasts of Greshornish Peninsula. Since these are markedly different values, an average is allocated to the centre-spot of group '3'.

The intensity of multiple-dykes increases towards the Central Complex of Skye, especially along N.N.W. to S.S.E. axial regions (fig.52). The axis of high-intensity to the south of the Complex is especially clear, although it tends towards division into northern Morar and into Arisaig. Multiple-dykes reach peak intensity on the eastern coast of

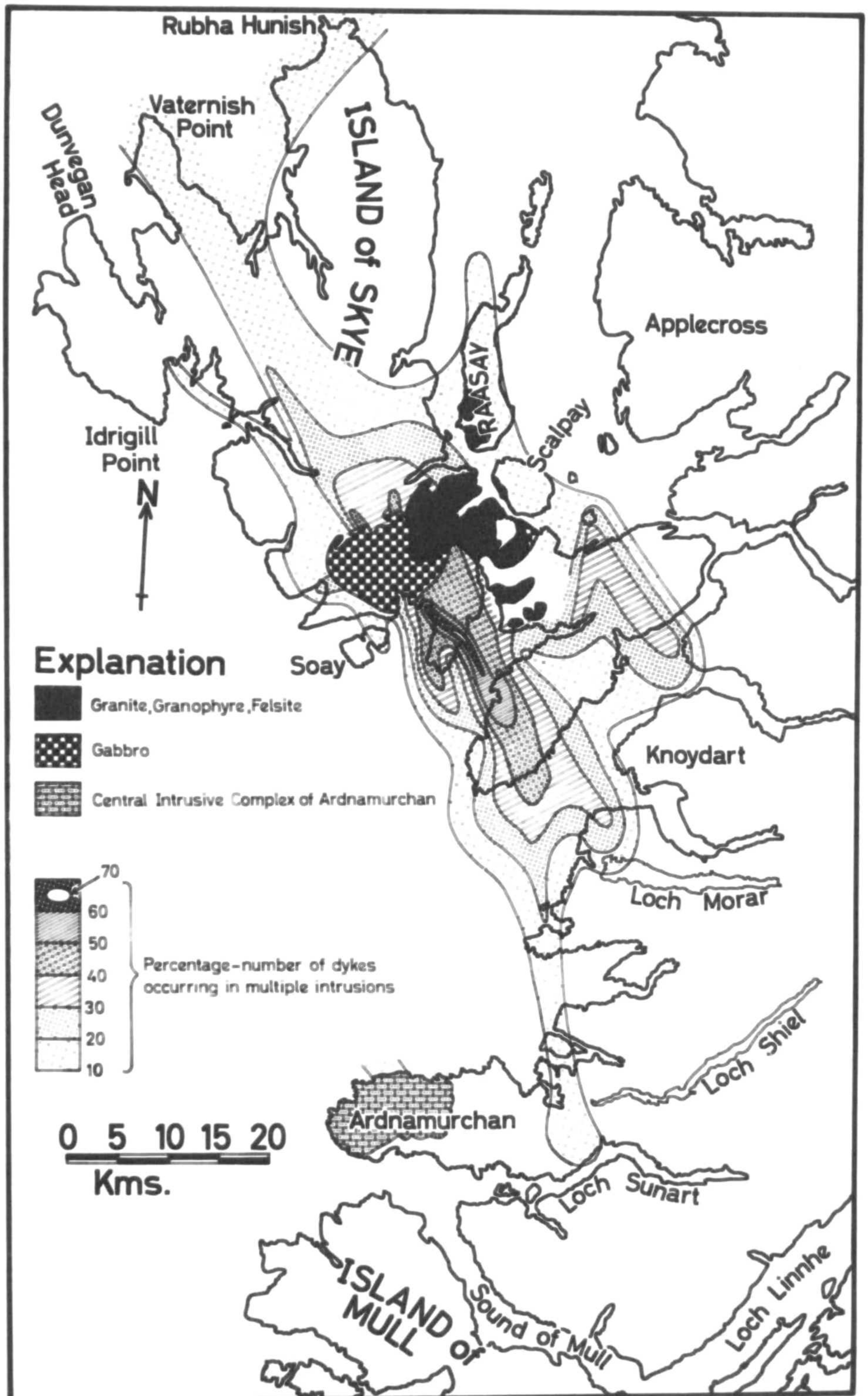


Fig.52. Map to show intensity and distribution of multiple dyke intrusions

Strathaird, and decrease slightly in abundance towards the Cuillins. There is some indication of branching of the main axis towards southern Strathaird.

In all other respects this axis of high proportions of multiple-dykes closely follows the line of the main dilation-axis in southern Skye and on the mainland (fig.48). Even the swing towards a N. to S. alignment is evident from Morar to Moidart (fig.52).

The number of multiple-dykes occurring to the north of the Central Complex of Skye is especially prominent along an axis extending to Vaternish Point, and again coincident in position with the main dilation-axis. A less pronounced axis of relative high intensities of multiple-dykes trends to the north, towards Portree Bay.

To the south-west of the Cuillins, intensities of multiple-intrusions are low, with only a slight prominence at the head of Loch Brittle. In east-central Skye, the distribution of the multiple-dykes reflects the location of the Scalpay Secondary-Swarm. The higher intensities are disposed along a N.N.W. axis passing from the Glenelg area through to Broadford Bay, and trending northwards through Raasay. The band of relatively high intensities from Broadford Bay to the head of Loch Eishort is coincident with the outcrops of "peripherally-folded" Jurassic sediments.

In Ardnamurchan, multiple-dykes are few and their distribution is variable (Appendix 10). There is some evidence that abundance increases near the location of the main dilation-axis on the north coast, although group 'AF', in a similar position on the south coast, includes no multiple-dykes.

Throughout this brief description of fig.52 comparison has been made with the axes of dilation map (fig.48). In many ways a better comparison is made with the intensity of dykes by number (fig.51). Clearly, in regions where the number of dykes is greater, the probability of the formation of multiple types is also greater. Such regions are those near to the Central Intrusive Complexes and to the axial regions of high-intensity by number.

"Grouping" of dykes is a phenomenon similar in some respects to multiple-dykes. In many traverses, apart from the congregations of several dykes as multiple-intrusions, there are also cases of the proximity of the outcrops of several single (or multiple) dykes, separated from another such group by long stretches with few or no dykes. This is found to be especially true in the coastal sections of Strathaird and Sleat. A quantitative study of this aspect of the distribution of the outcrops is not undertaken. This is because of the enormous amount of labour and time, which the accurate measurement of many kilometres of section involves.

On a semi-quantitative level it can be said that "grouping" becomes a more frequent and better-developed phenomenon closer to the Central Intrusive Complex of Skye. This is especially true to the south-east of the Complex, in Strathaird and somewhat less so in Sleat. It would not be surprising to find that a statistical analysis would reveal a close correspondence between the intensity of multiple-dykes and the frequency of the "grouping" of dykes.

In many examples the distance between dykes in a "grouping" is only a few metres or even centimetres. The reason for this slight separation may be that the country-rock close to the margins of a dyke suffered a thermal-shock, during emplacement of the dyke. In some cases, this could have increased the resistance of the country-rock to further fissuring at these localities. There is, unfortunately, little direct evidence to support or nullify this postulation.

In as much as multiple-dykes and the "grouping" of dykes occur in the same region, there is some contradiction of the latter hypothesis, for their mechanisms of formation are opposed. A later dyke of a multiple-intrusion follows the line of weakness of the first intrusion. Conversely, a younger dyke in a closely grouped assemblage is separated from an older dyke by a band of country-rock resistant to fissuring at the margin of the older dyke. Clearly there is an anomaly between the two explanations. It remains inexplicable until detailed analyses of the physical properties of the country-rock, at successively greater distances from the margin of a dyke, can be made.

8:III. Multiple-Dykes of the Subswarms.

Two dykes are found in a multiple-intrusion out of 100 observed dykes in the Glenbrittle-Subswarm. This contrasts with an average of 10 per cent. for groups '18','19','19A', '20', and '0B', of dykes in the linear-swarm in the same area (Appendix 10).

A multiple-intrusion consisting of two dykes, among 39 recorded dykes of the Scalpay-Subswarm, is equivalent to 5 per cent., and contrasts with an average of about 15 per cent. for groups '11' and '12' in the same area (Appendix 10).

Eight out of 121 dykes in the Broadford Bay-Applecross Subswarm are involved in multiple-intrusion. This is equivalent to 7 per cent., and again differs from the average of 25 per cent. for groups '34','45', and '46', in the Rubha Suisnish and Broadford Bay districts (Appendix 10).

In general, then, the frequency of multiple-dykes in the subswarms is comparatively low. This in many respects again is an expected result, since the intensity of the dykes in the subswarms is also low.

Chapter Nine

THE THICKNESSES OF THE DYKES

9:I. Introduction.

Measurement of the thicknesses of individual dykes is occasionally fraught with difficulties. Although the dykes have a fairly constant thickness, in some cases there is variability (say, up to 10 per cent.) along the direction of the strike or dip of the dykes. Poor exposure in either or both of these directions reduces the accuracy of observation of a mean value of the thickness.

The thickness is quoted in most cases to the nearest 5cm., since this is considered to be a normal range of error. The thickness of very narrow dykes (say, less than 10cm.) is taken to the nearest centimetre. The problems encountered in the measurement of very broad dykes (say, over 10m.) increase the margin of error up to a third or even half a metre.

9:II. The Thicknesses of Dykes of the Regional Linear-Swarm.

A preliminary analysis of the data is in the groups of 100 or 50 dykes. Appendix 11 is a table of the frequency-distribution of the thickness of the dykes, in half-metre intervals below 5m. thickness. Dykes of greater than 5m. thickness are far fewer in number than those of lesser breadth. The measurement of such broad dykes to within 5cm. is difficult. Hence, to allocate a dyke, for example about five-and-a-half metres thick, to the half-metre range either side of that value, is not easy. In consequence, the breakdown into whole metre intervals for the broader dykes is preferable.

The more commonly-occurring and the more easily-measured widths of less than 5m. are best analysed in the more informative half-metre intervals.

The frequency-distribution values in Appendix 11 total 100 or 50, but the histograms based on them (figs. 53 to 71) are constructed on the basis of 100 for each group, i.e. on a percentage-basis. In these histograms, any one dyke in an interval above 5m. thickness is plotted as if it were half a dyke covering the whole of the one-metre range of that interval. This maintains equal-areas throughout all the histograms.

It is proposed to relate only the main inferences derivable from the fairly detailed analyses, illustrated by the histograms. To describe each analysis in detail would be both laborious and tedious. The following brief description of the histograms depicts the general: the presentation of Appendix 11 and figs. 53 to 71 satisfy the requirement that the particular should also be portrayed.

In the northern districts of Skye and in Raasay, the spread of the thicknesses of the dykes is small, with most thicknesses less than 3m. and with a predominance in the half- to two-metre range (figs. 53, 54, and '5A' and '5B' on fig.56). Closer to the Central Intrusive Complex of Skye, the spread is yet narrower, with very many dykes of thickness of less than one-metre, with especial prevalence in the half- to one-metre range (figs. 55, 57, 58, and '16','17','11' on fig.56).

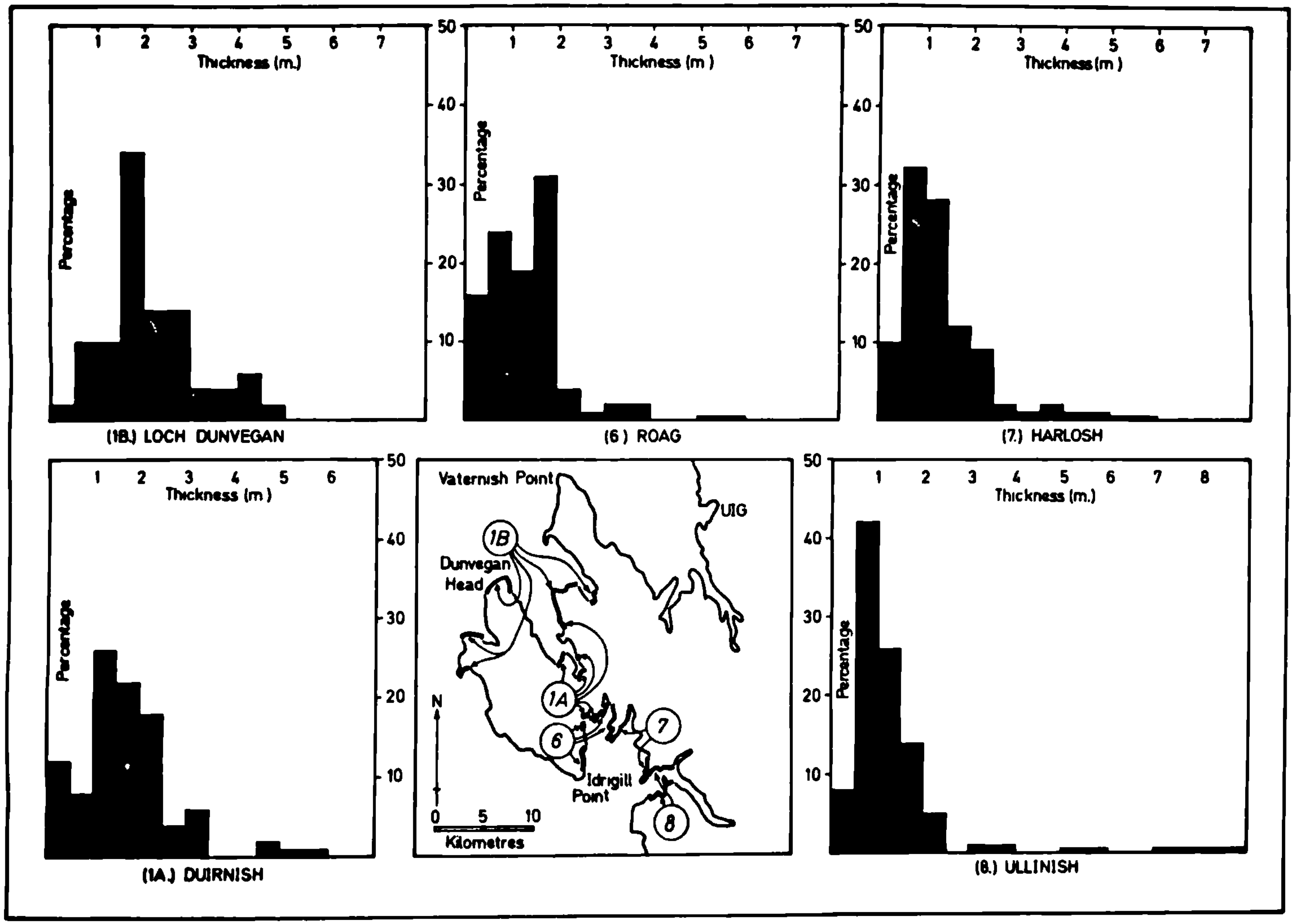


Fig.53. Thickness-analysis

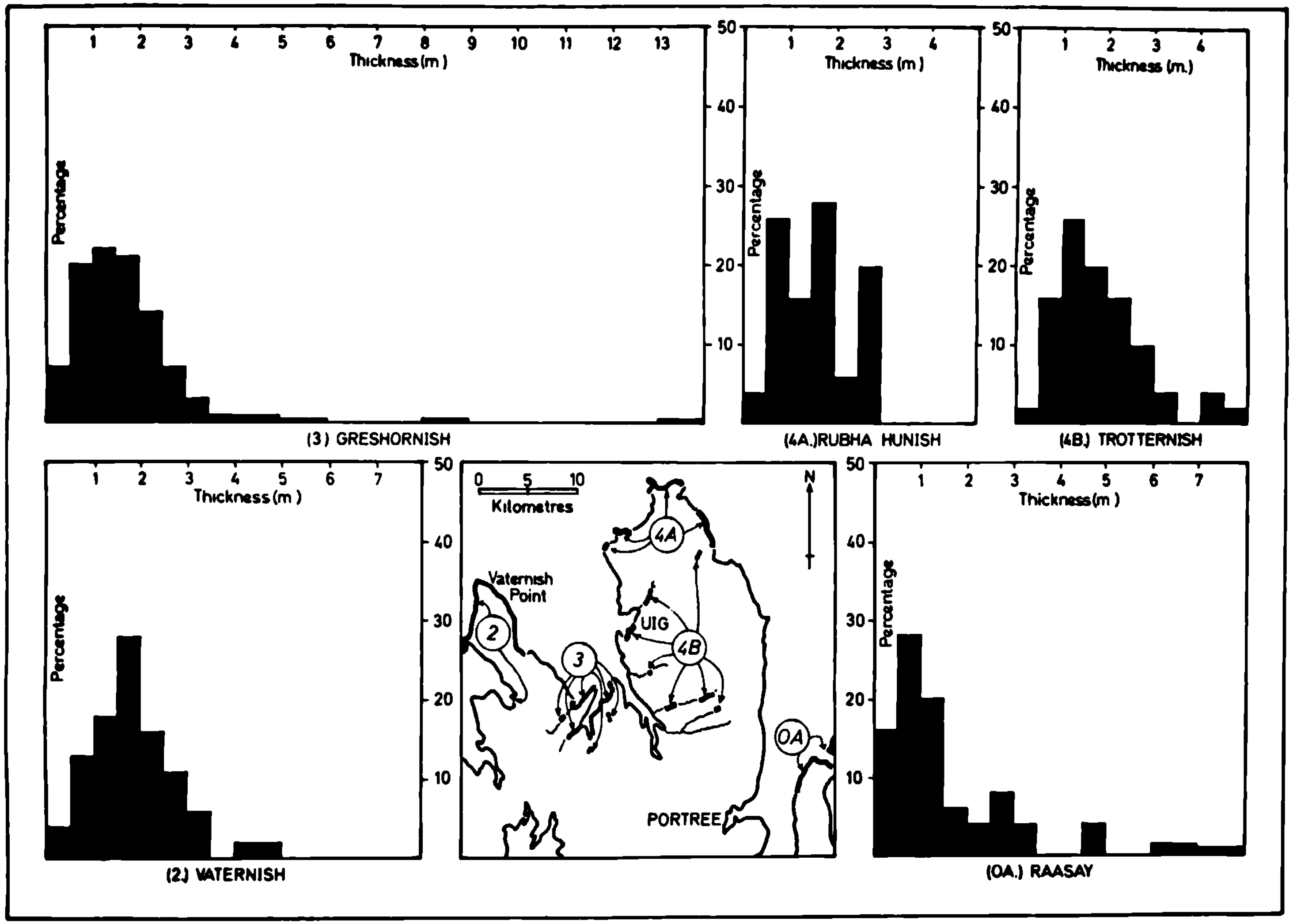


Fig.54. Thickness-analysis

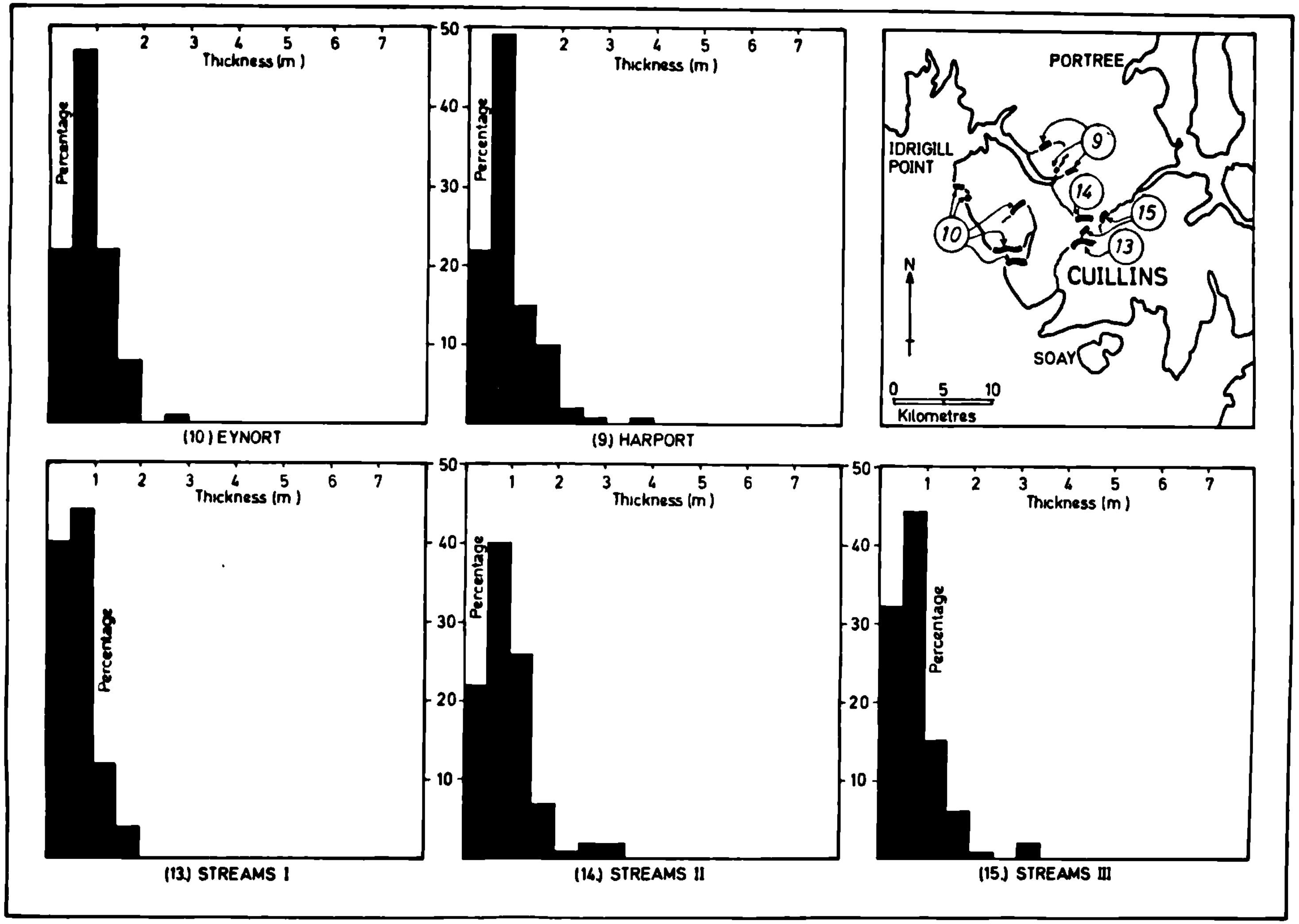


Fig.55. Thickness-analysis

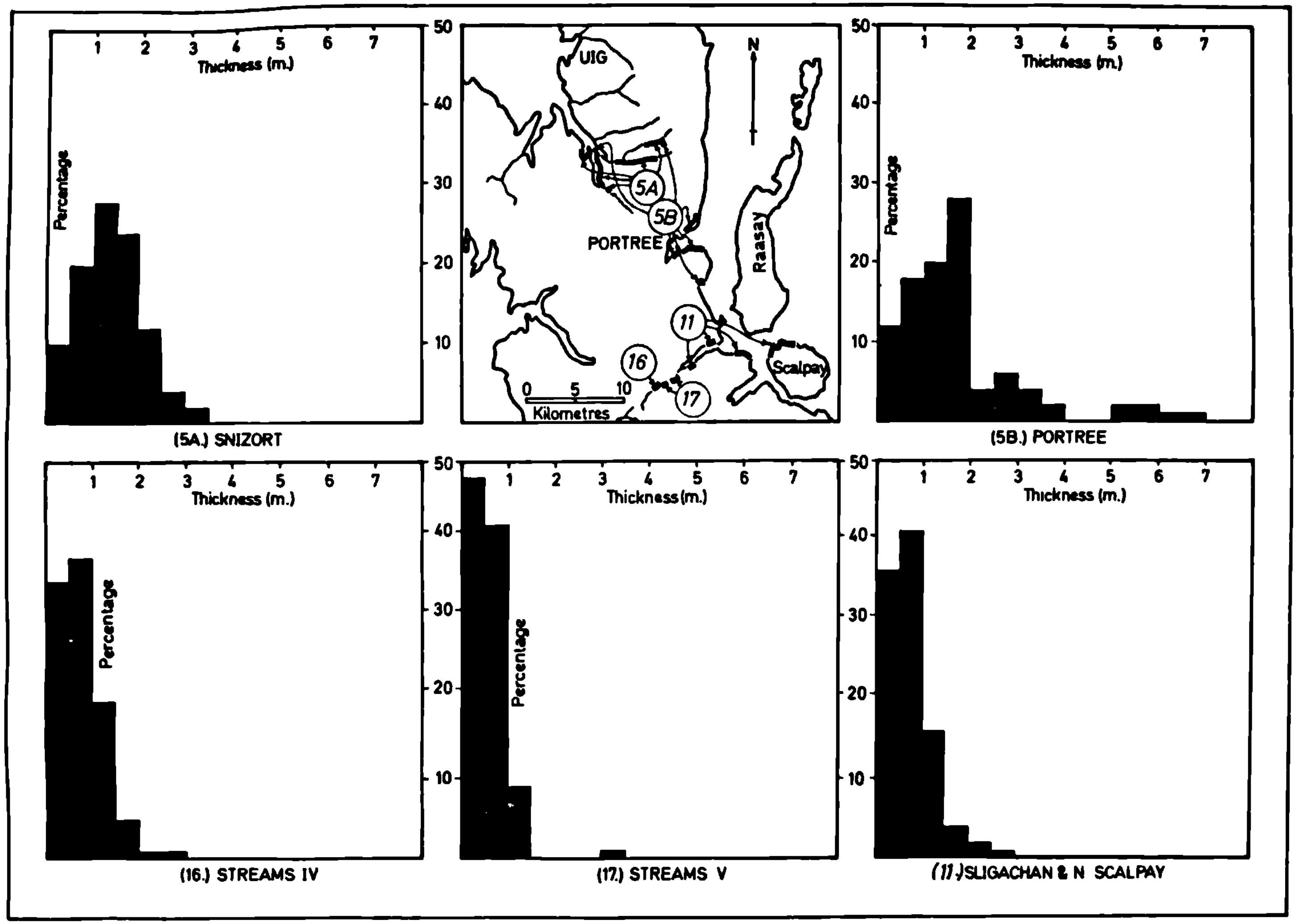


Fig.56. Thickness-analysis

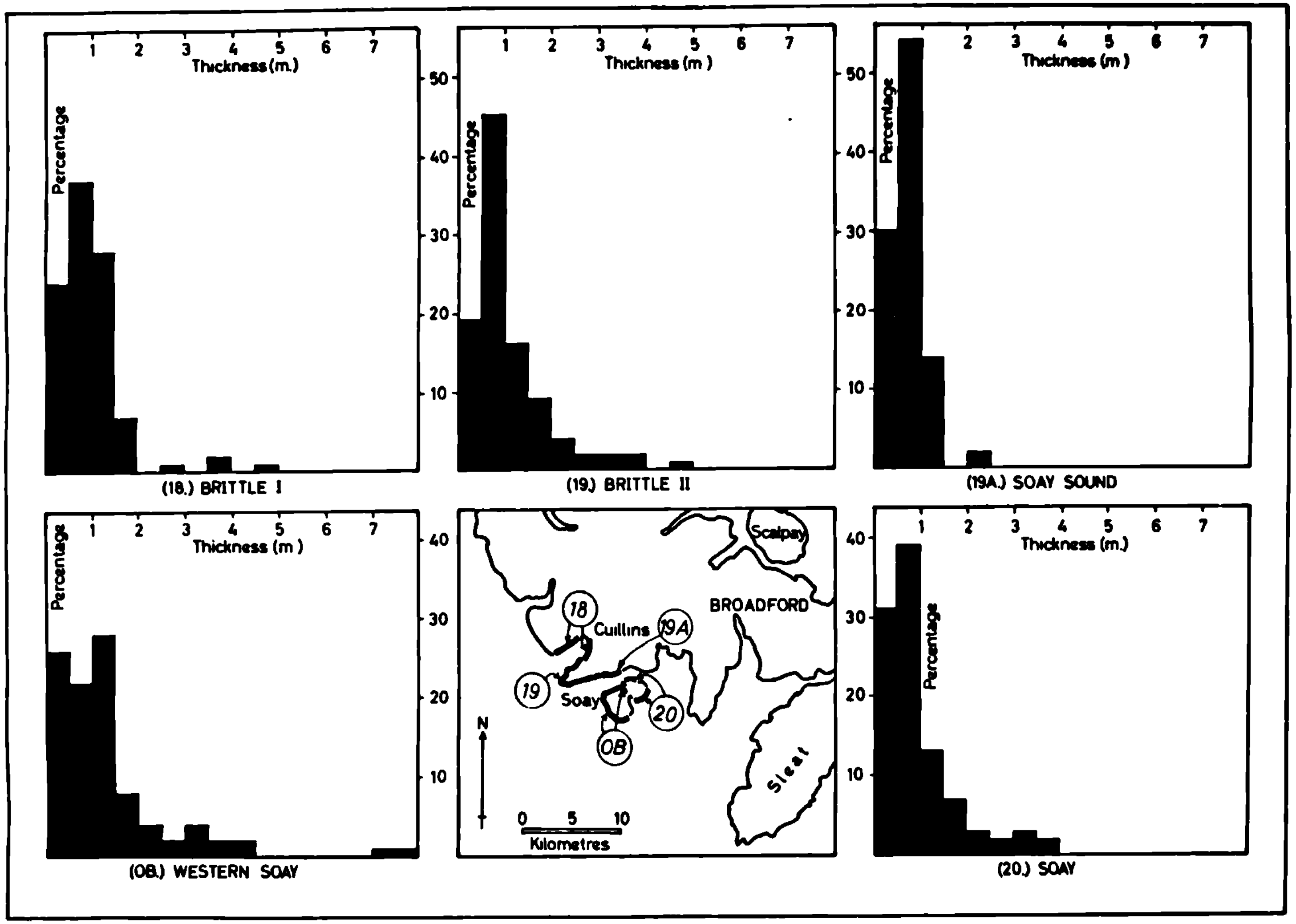


Fig.57. Thickness-analysis

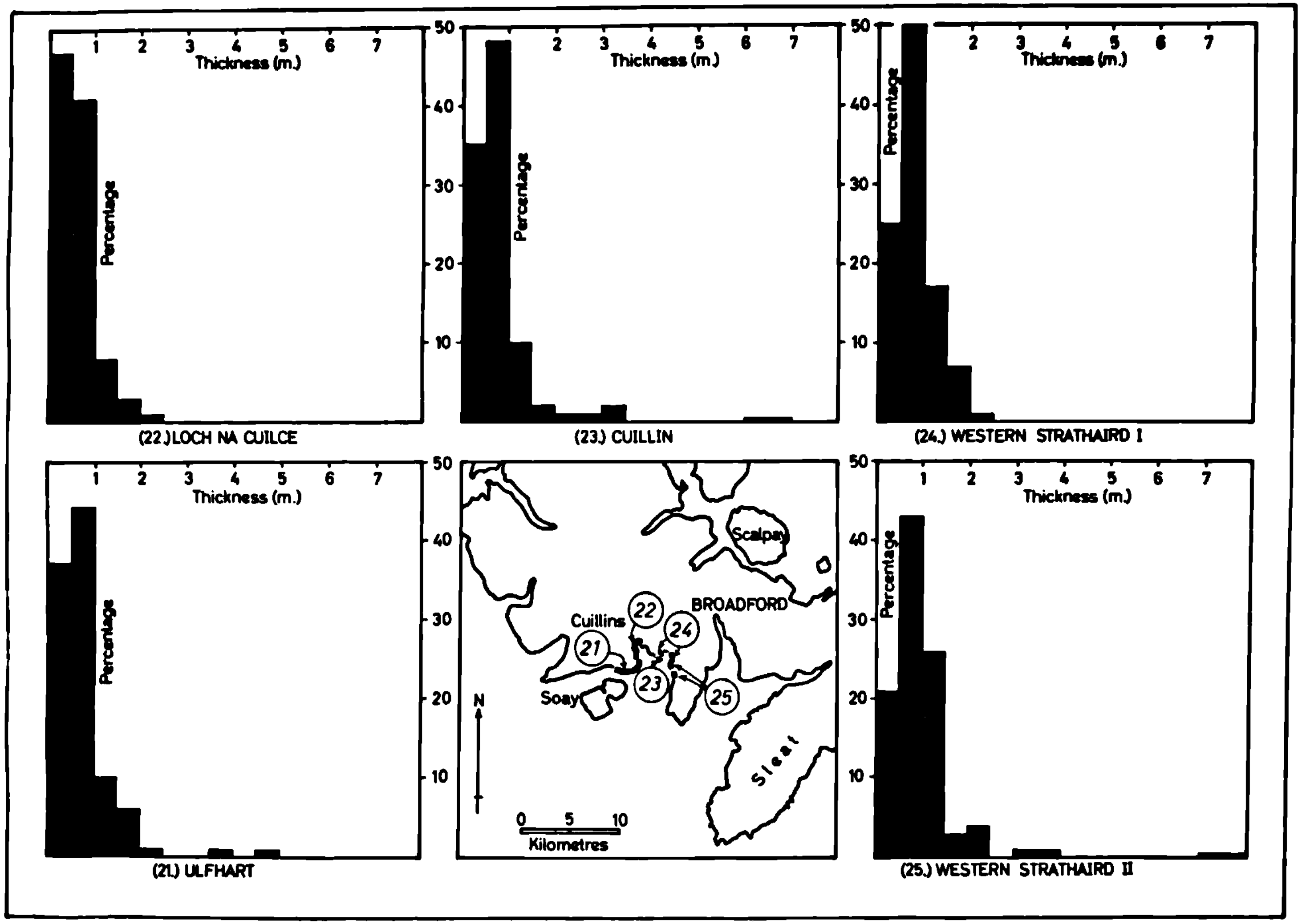


Fig.58. Thickness-analysis

In most of the groups on Strathaird, the spread is slightly greater, with many dykes less than 1½ metres (figs. 59 and 60). Groups on Loch Eishort (i.e. '34' and '35'), and near Broadford Bay (i.e. '45' and '46'), and the Ainort and southern Scalpay group ('12') (fig.61), have dykes with a similar spread of thicknesses to those in Strathaird.

Turning attention to the south of Skye, groups in northern Sleat show a large and even spread of thicknesses below 2m., with dykes above 5m. thickness more frequent than in previously described groups, especially in group '38' (fig.62). In southern Sleat the spread of thicknesses ranges evenly up to 3½ metres, and is especially even in group '42' (fig.63 and part of fig.64). Yet on the adjacent mainland (in groups 'OD' and 'OC',fig.64), the spread of thicknesses is small and the dykes are more frequently thinner than in southern Sleat.

South of the Mallaig district, the spread of the thicknesses is again broad and fairly even, with a very much more common occurrence of the very wide dykes (figs. 65 to 68). Yet farther south, the narrower dykes increase in abundance at the expense of the broad dykes (fig.69).

On Ardnamurchan, the six groups (figs. 70 & 71) show a quite variable frequency-distribution of thickness, with a fair abundance of dykes of less than one-metre breadth, but also occasional dykes of greater than 5m. thickness.

There appears to be some regular pattern in the geog-

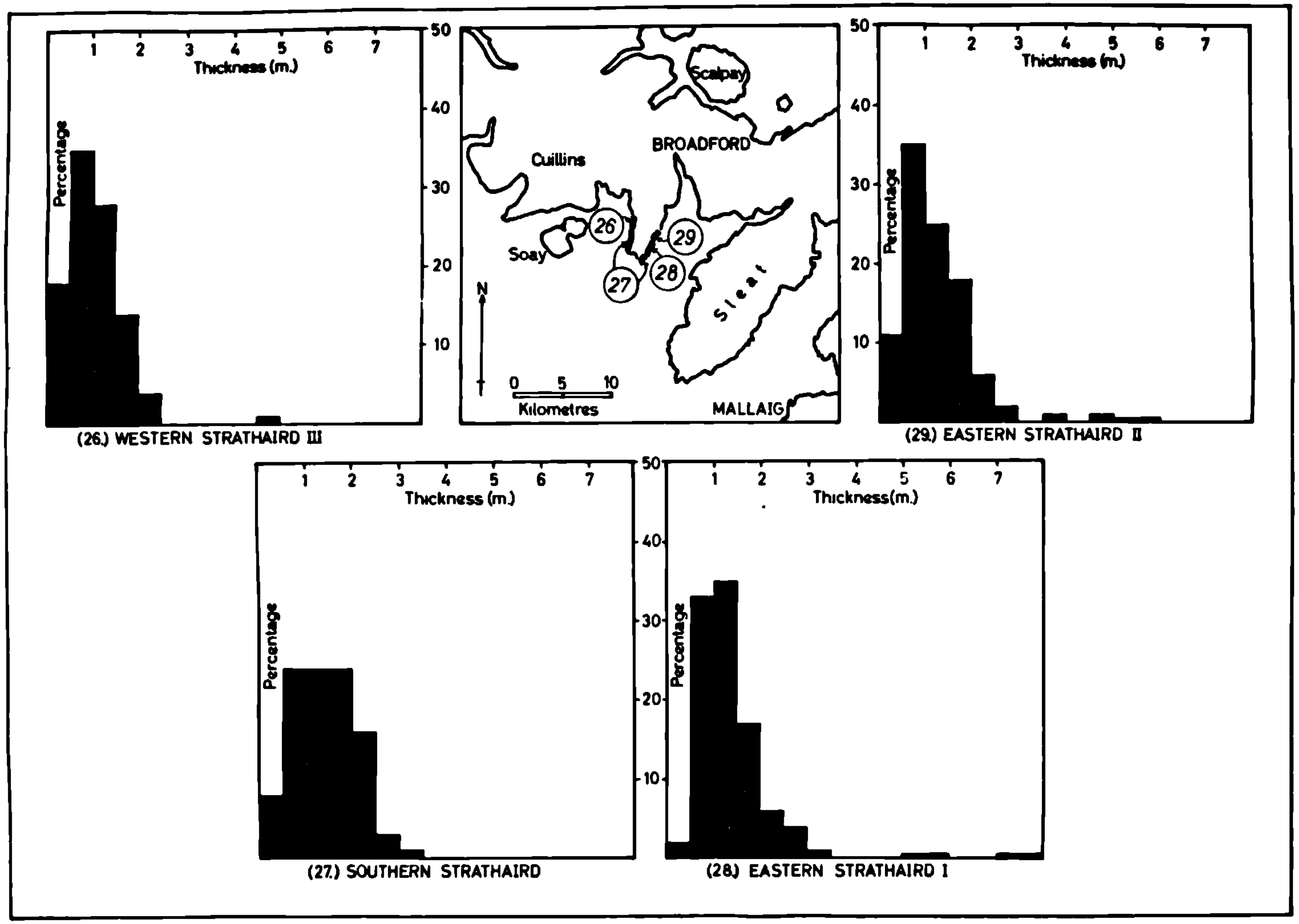


Fig.59. Thickness-analysis

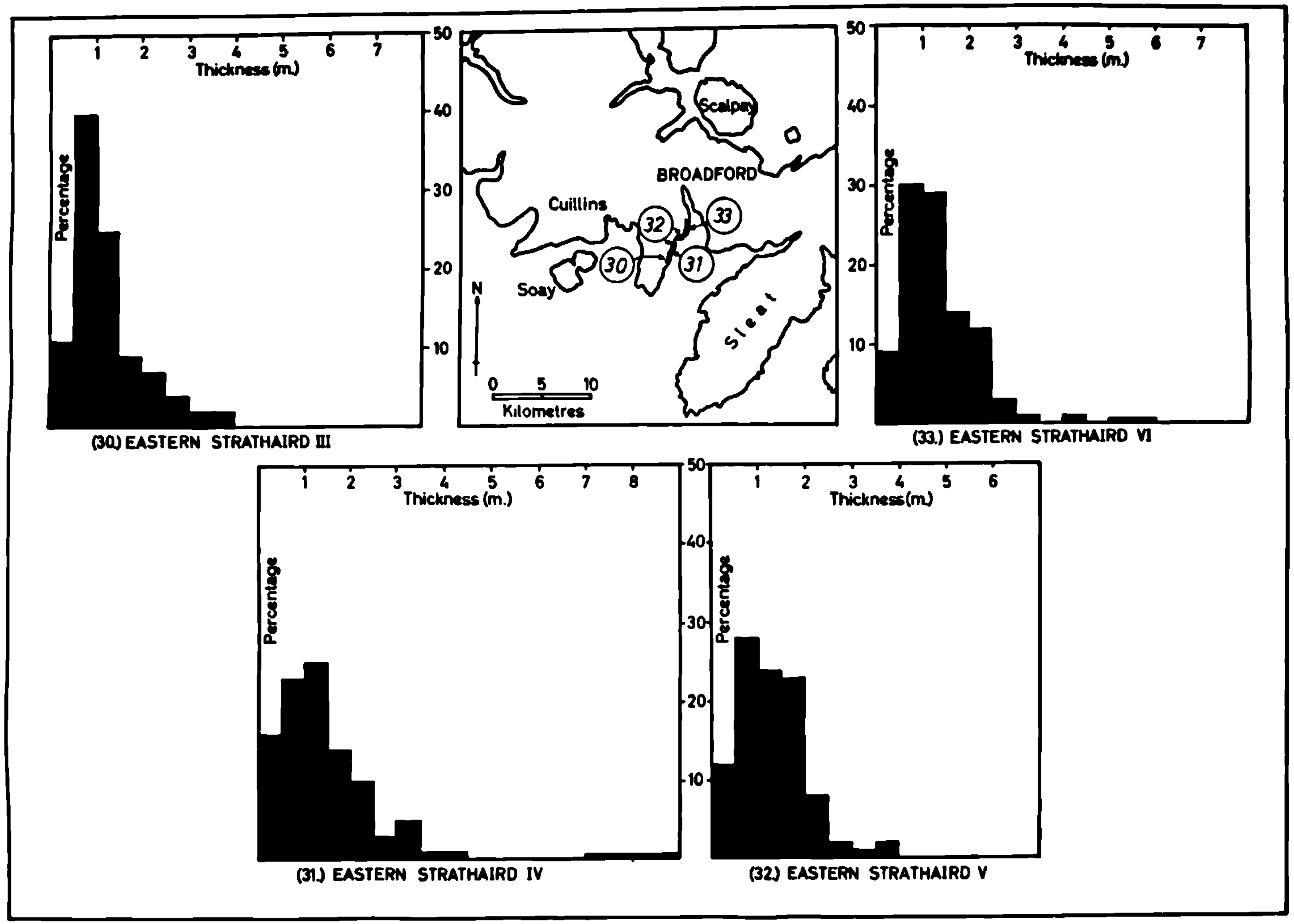


Fig.60. Thickness-analysis

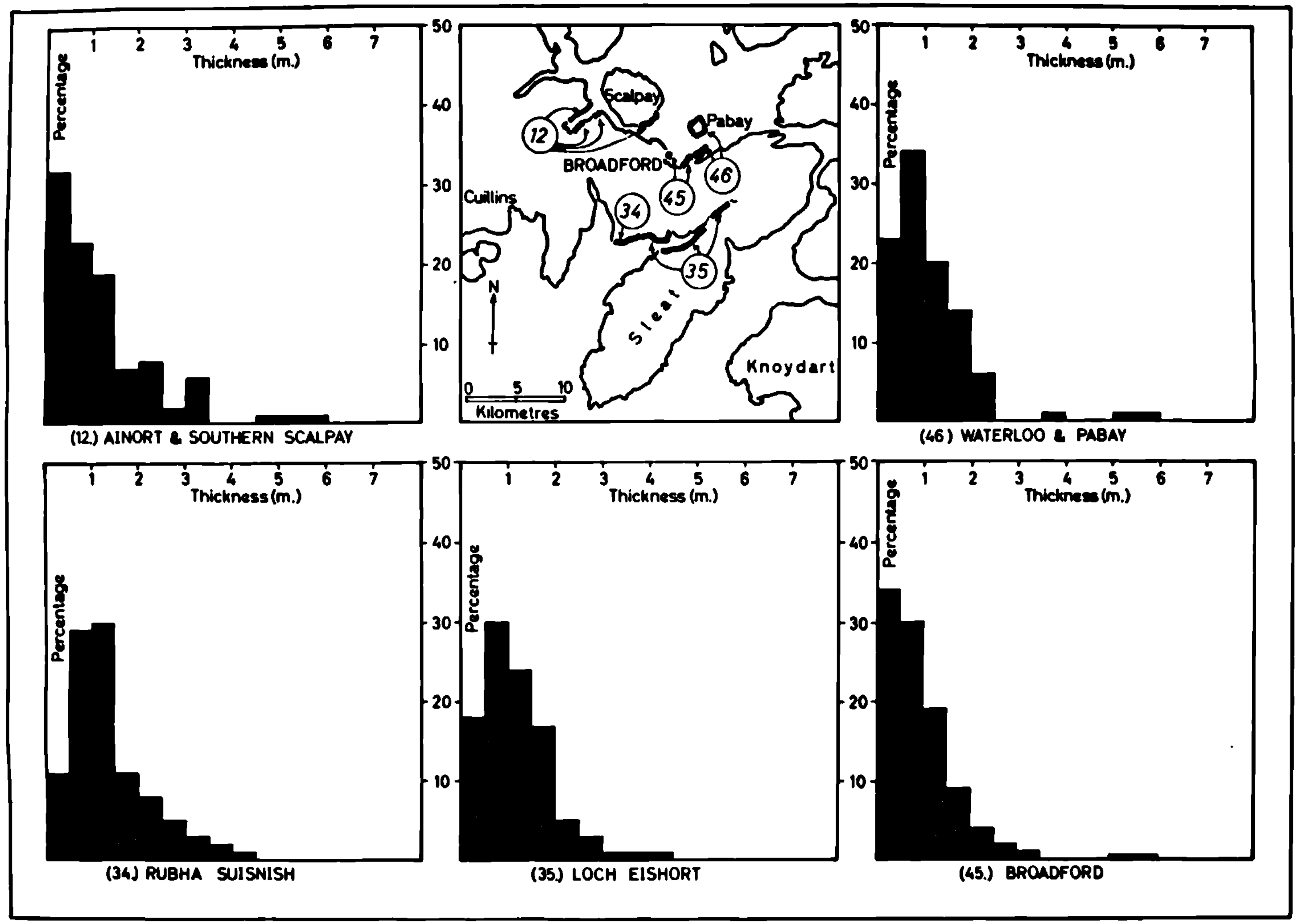


Fig. 61. Thickness-analysis

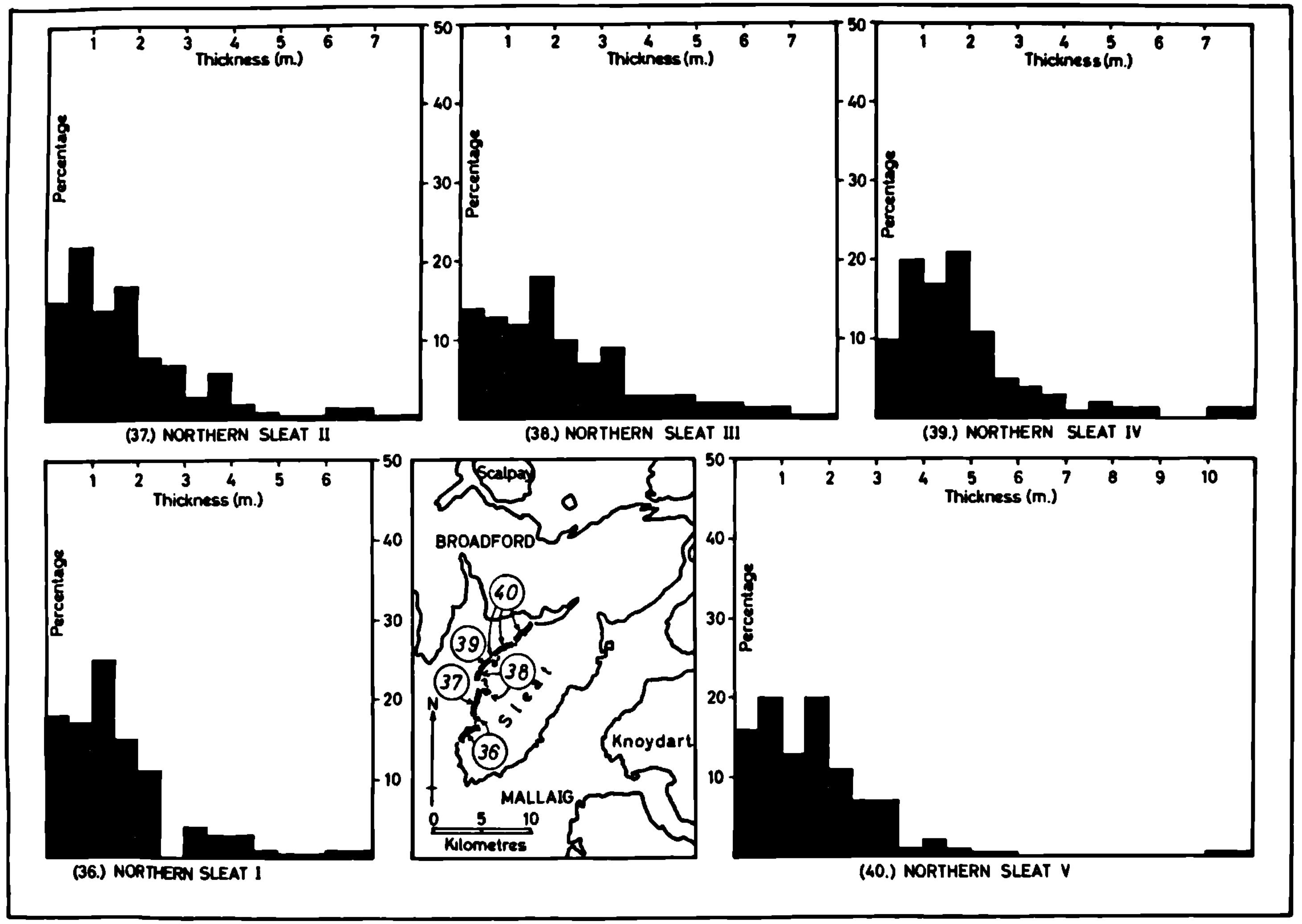


Fig.62. Thickness-analysis

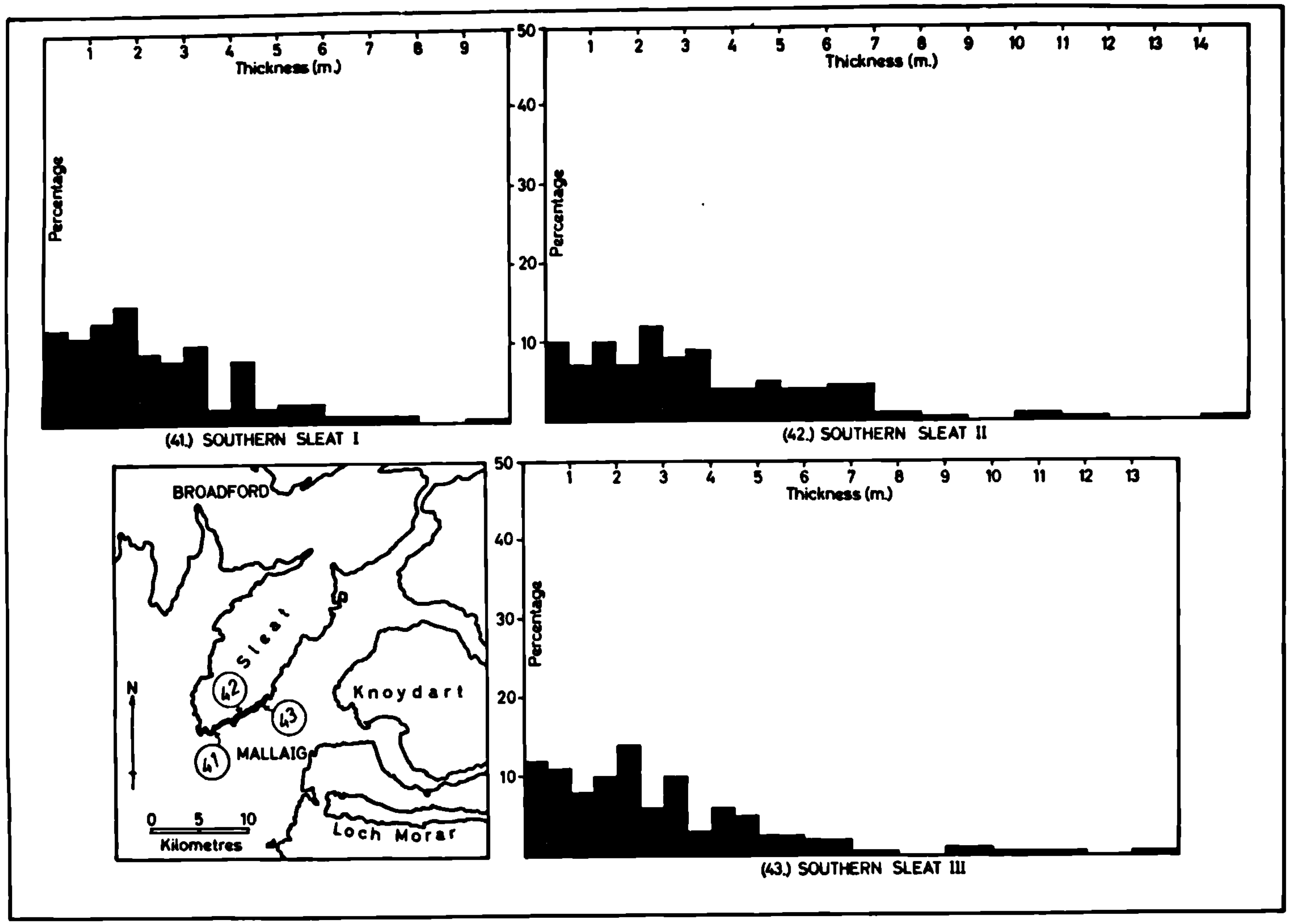


Fig.63. Thickness-analysis

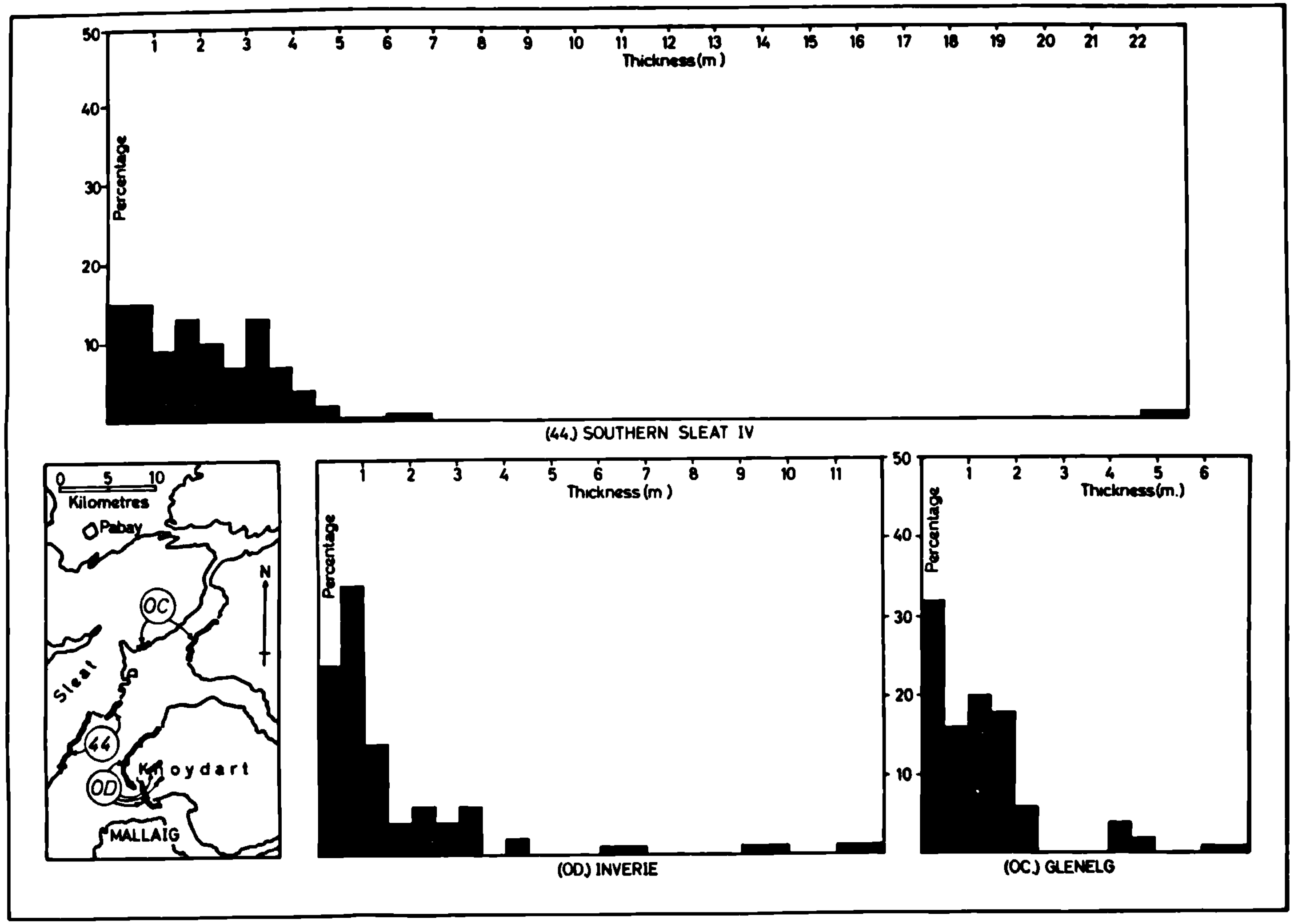


Fig.64. Thickness-analysis

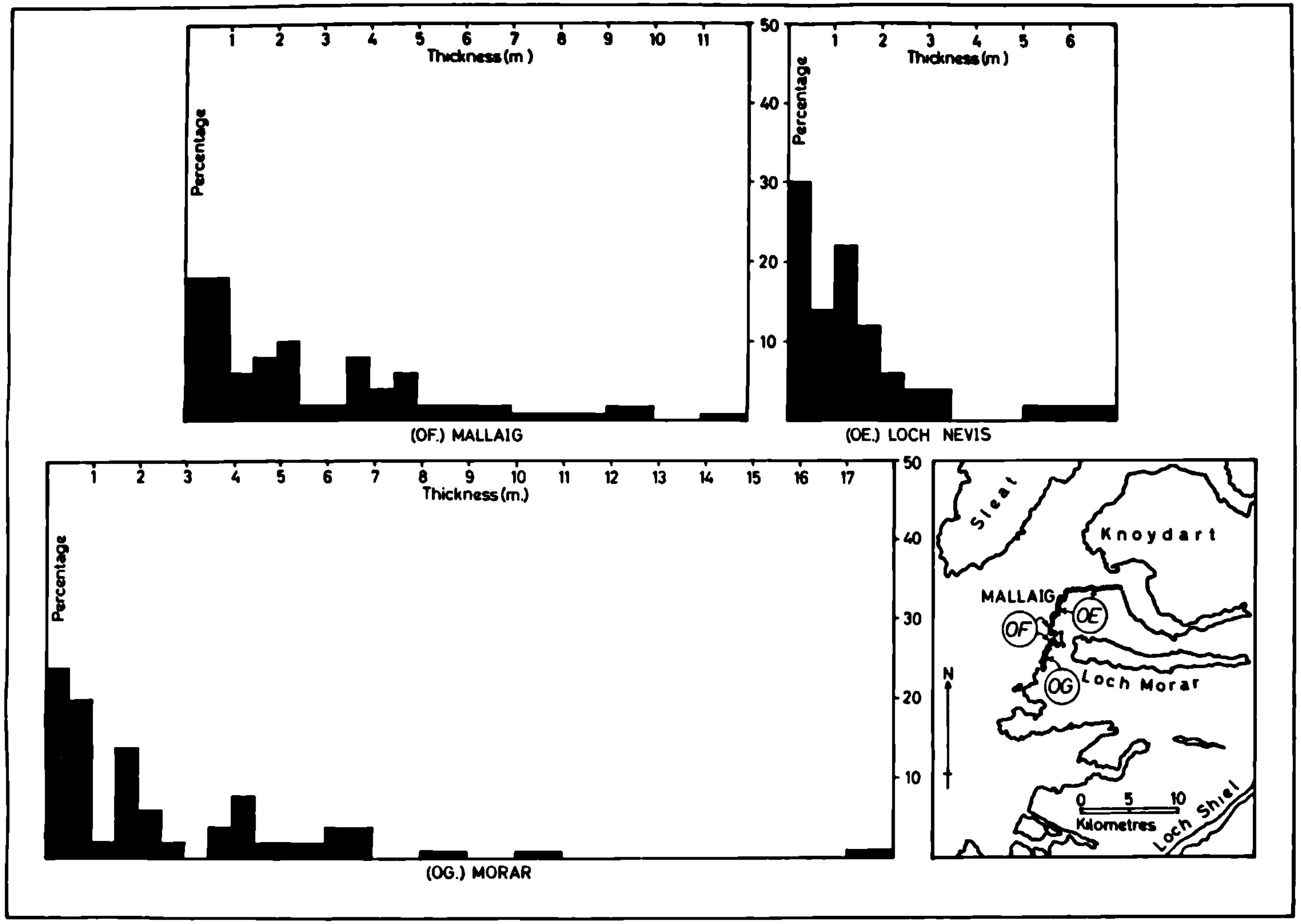


Fig.65. Thickness-analysis

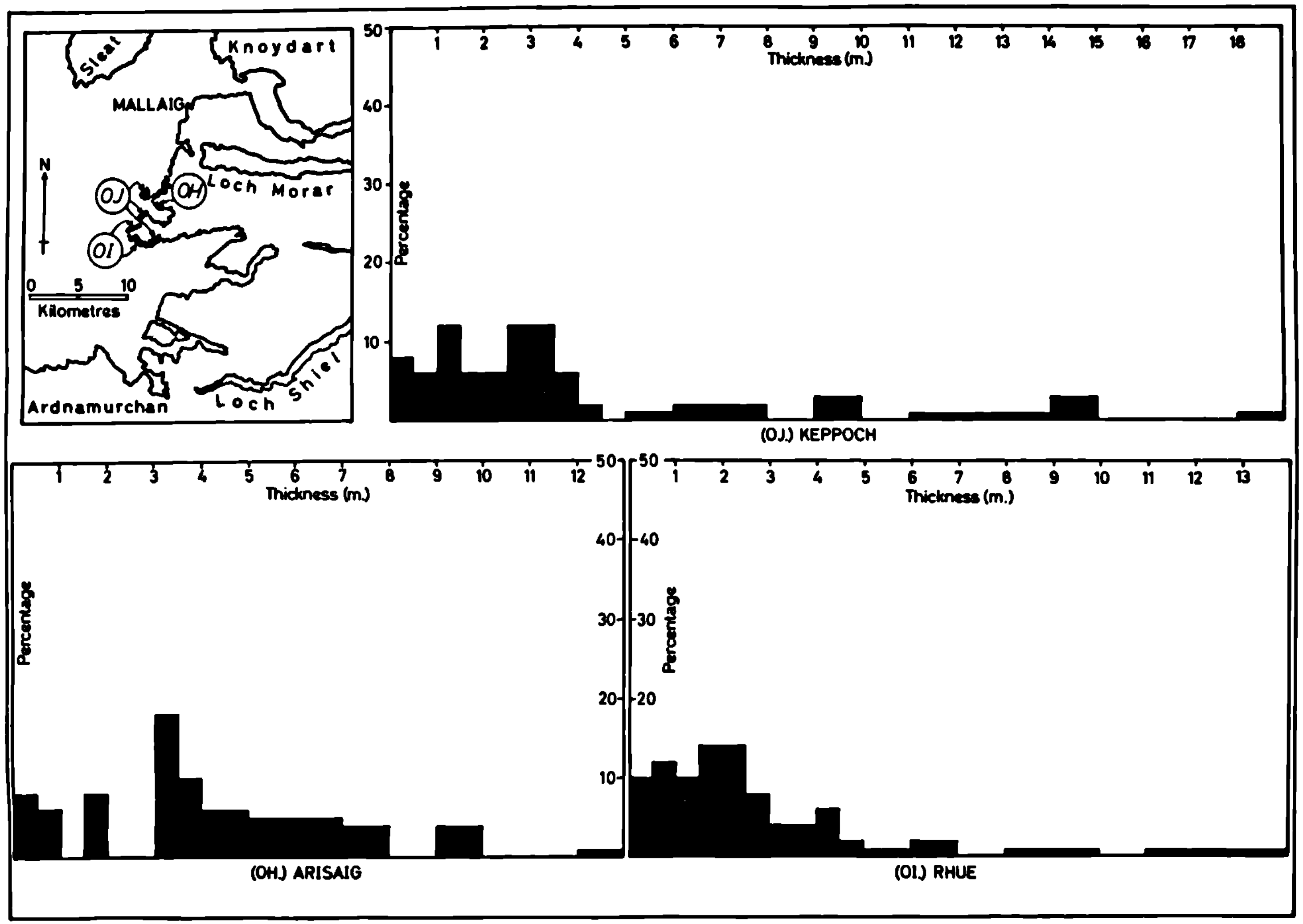


Fig. 66. Thickness-analysis

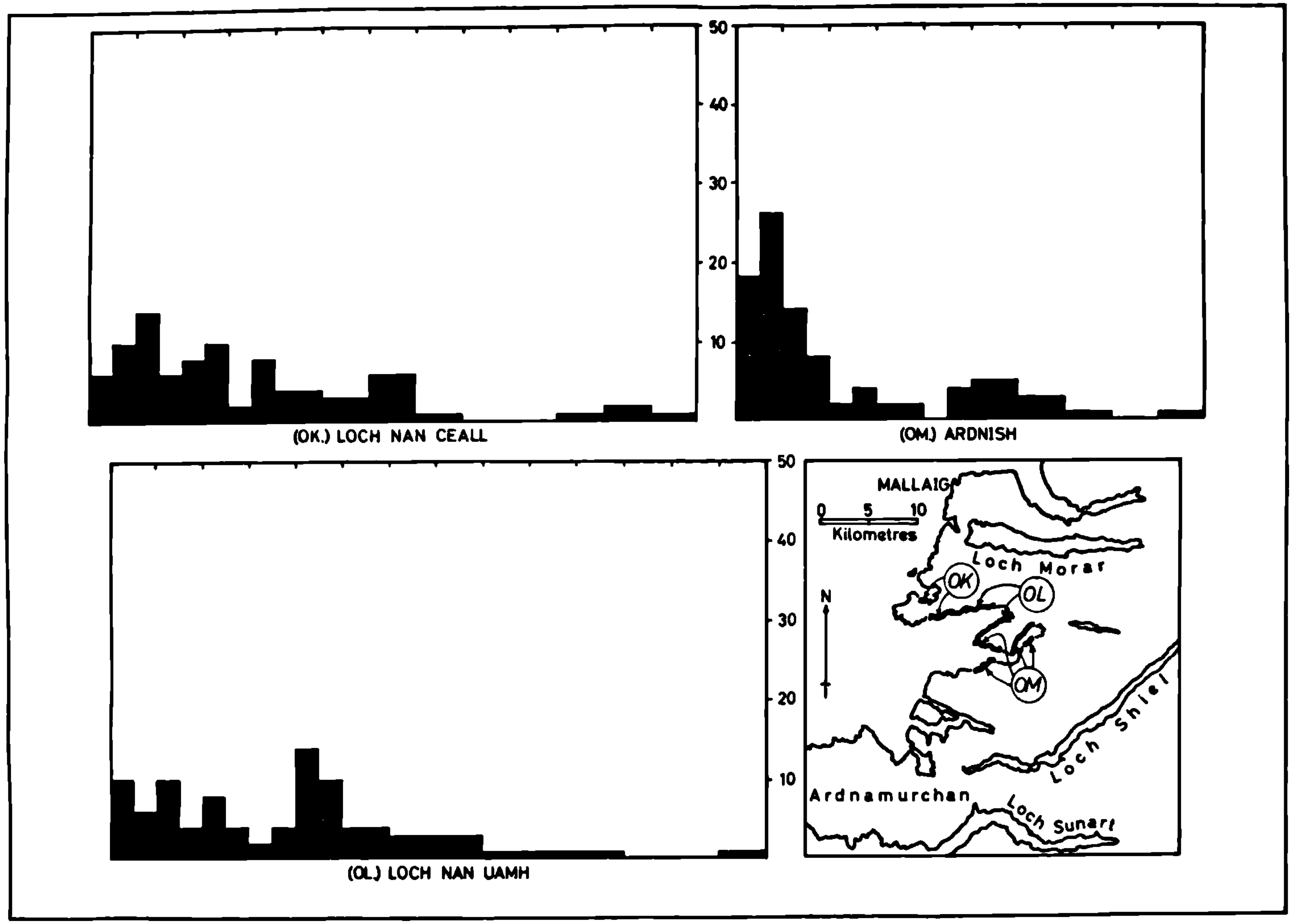


Fig.67. Thickness-analysis

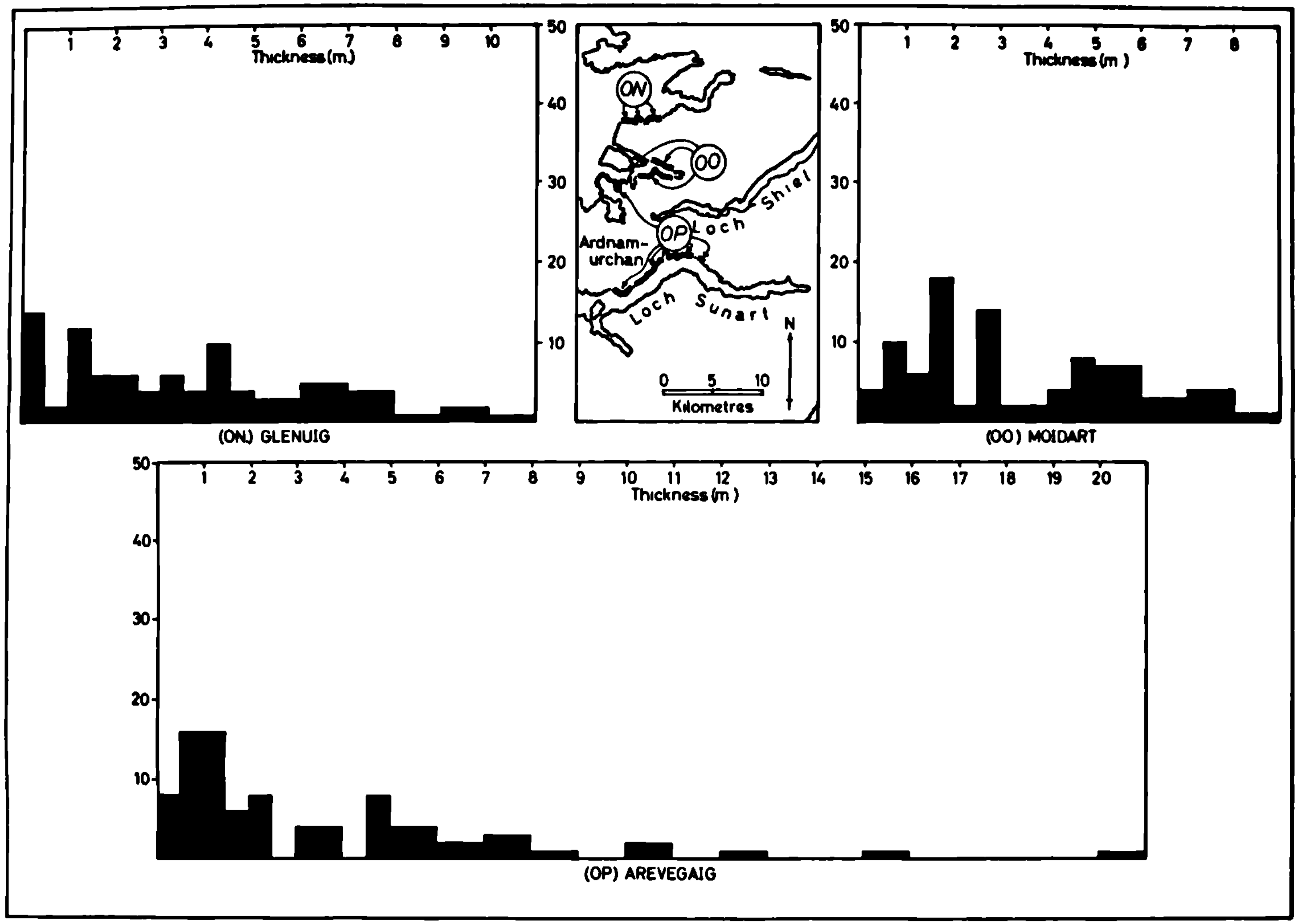


Fig.68. Thickness-analysis

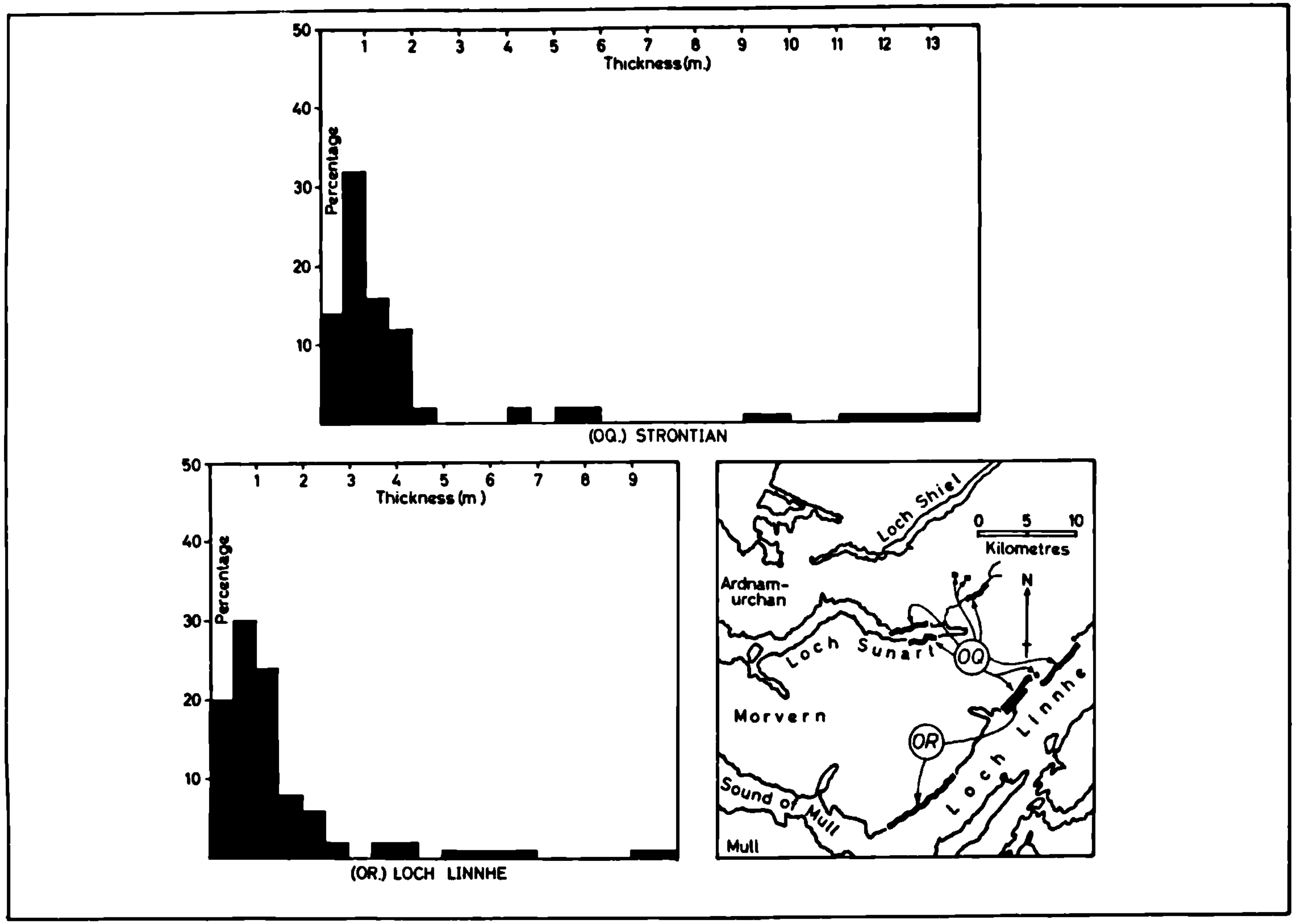


Fig.69. Thickness-analysis

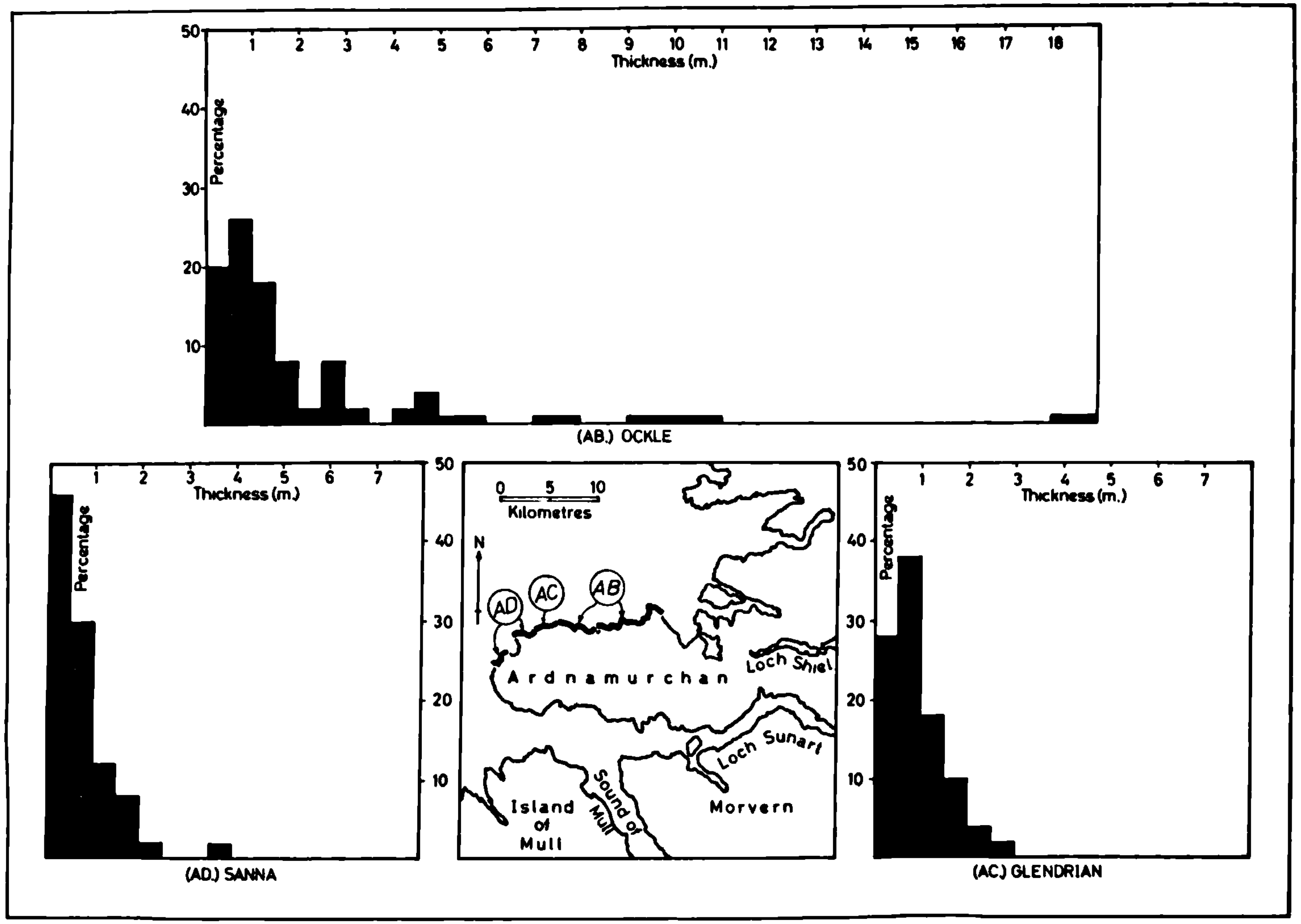


Fig. 70. Thickness-analysis

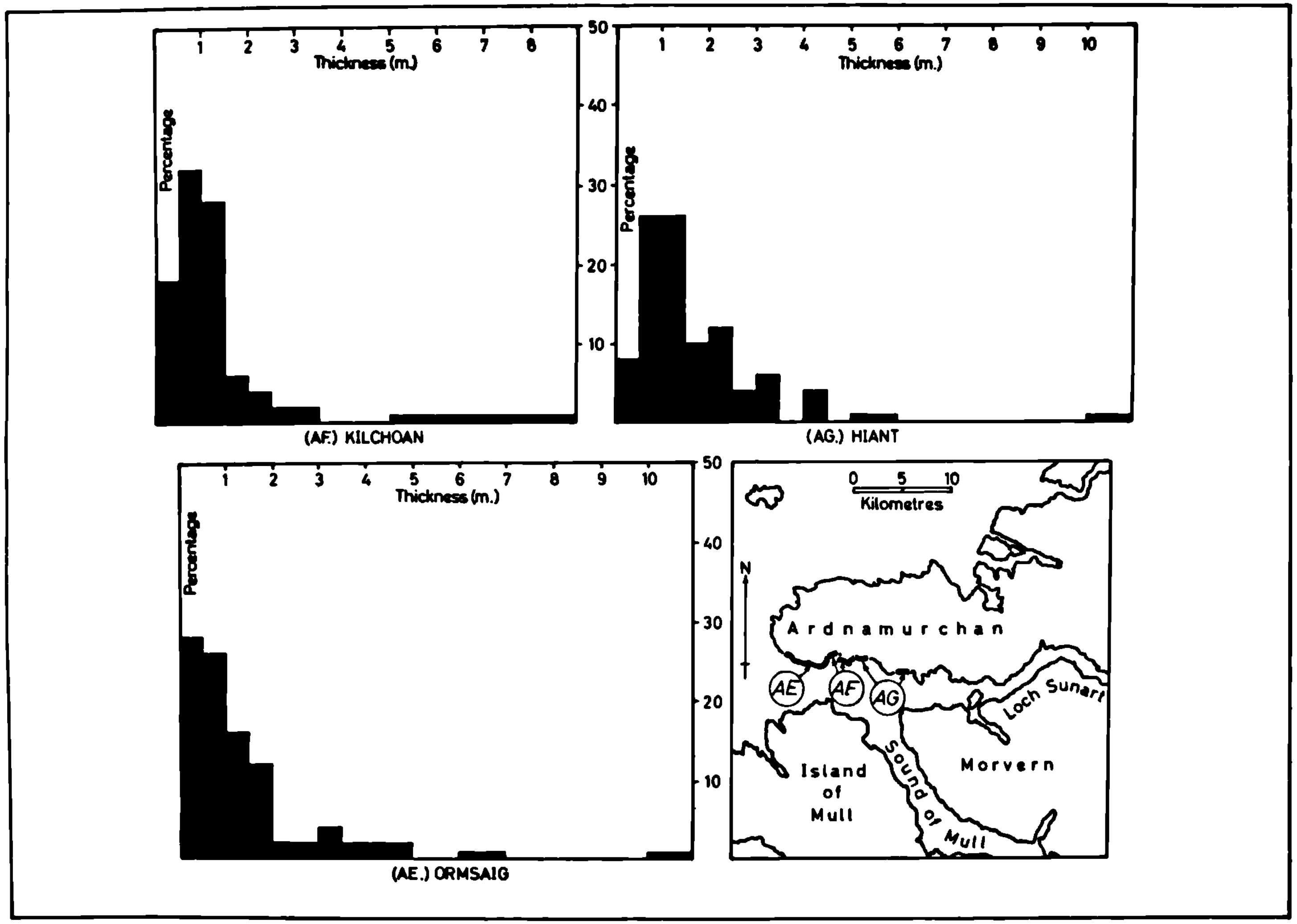


Fig. 71. Thickness-analysis

raphical distribution of dykes of certain thicknesses, for the Skye-Swarm at least. Dykes of less than one-metre breadth are widespread, but increase in relative abundance in regions near the Central Intrusive Complex of Skye. Dykes of greater widths become increasingly more frequent the farther is the distance between their locations and the Central Complex. The variation of the arithmetic-average thickness of the dykes (fig.72) demonstrates, in the simplest manner, certain of these aspects, although it does not indicate the details of the spread of dyke-thicknesses in any one region.

Fig.72 is contoured on the basis of plots of values of arithmetic-average thicknesses (for dykes of the regional linear-swarm) at the centre-spots of the 74 groups. The frequency-distribution graphs are hardly Gaussian in nature, and the marked lack of correlation between the arithmetic-mean, the median and the geometric-mean values of thickness in many groups (Appendix 10) also illustrates this fact. Undoubtedly, an arithmetic-average has consequently little statistical validity, and yet fig.72 possesses some interpretable patterns of distribution.

The rate of change of the average thickness northwards from the Central Complex of Skye, throughout the lava-terrain, is far less than that to the south through pre-Tertiary country-rocks. Minimal average thicknesses are located near the Central Complex; and everywhere away from the district of

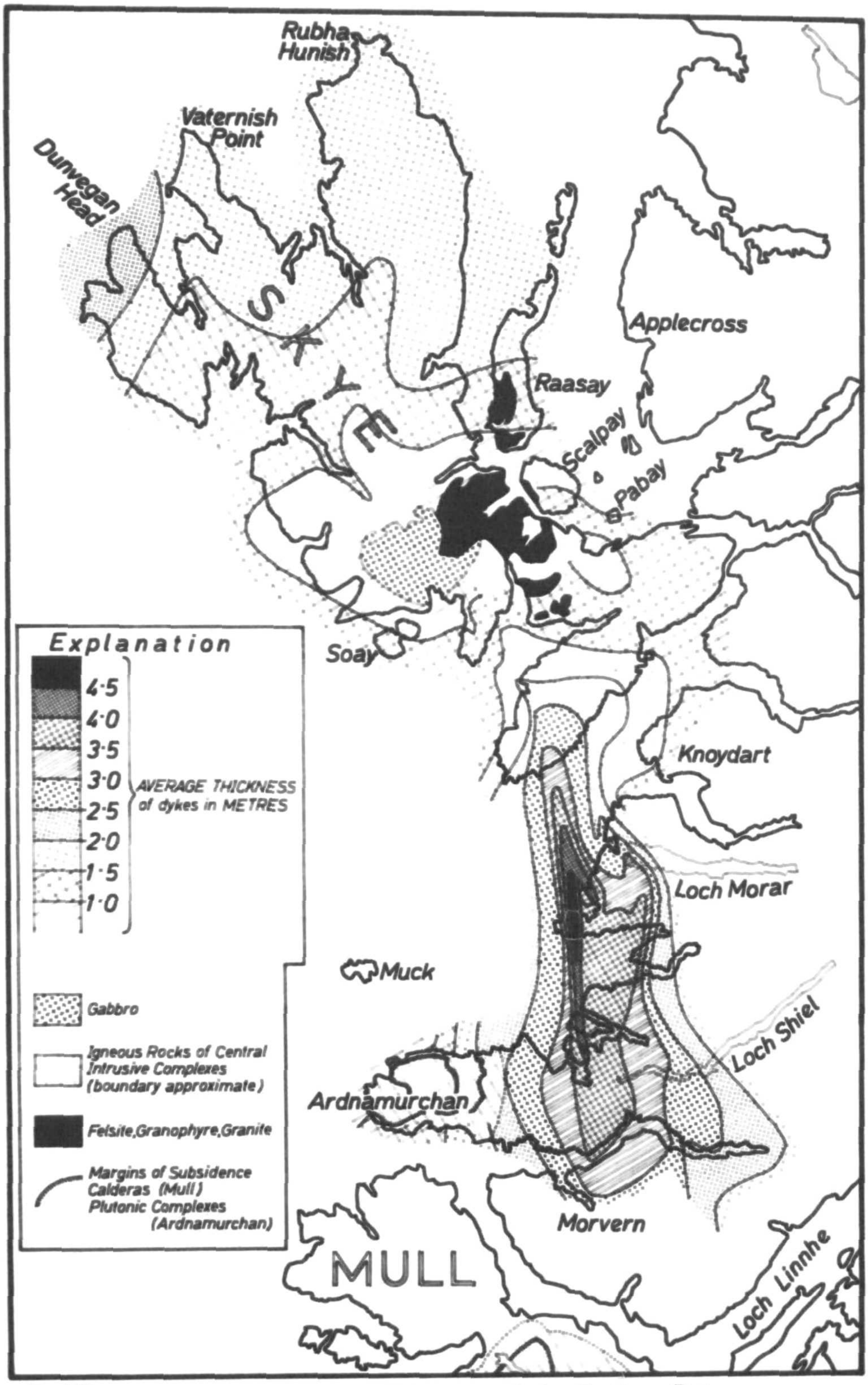


Fig. 72. Variation in the Average Thickness of the Tertiary Dykes

the Central Complex values rise. To the south of the Complex the distribution of the values indicates the presence of an axis of greater values, trending N.N.W. from Strathaird through Sleat, and trending N. to S. through Moidart to Sunart. This axis is approximately coincident in position with the dilation-axis through the same districts. Such an axis is not as prominently developed within the distribution of the average thickness to the north of the Central Intrusive Complex.

Average thicknesses, therefore, decrease towards the Central Complex of Skye, and increase towards the axes of dilation of the Skye-Swarm, especially to the south of the Complex. A maximum average value is attained in the Arisaig region. To the south of this district, the average thickness decreases through Morvern towards the Mull-Swarm. In Ardnamurchan, the maximum average thicknesses are located in areas through which the major axes of dilation pass.

The arithmetic-average thickness of seventeen dykes on parts of the south-east coast of Harris is 2.4m., a value in accord with a location near a dilation-axis and at a great distance from the Central Complex.

Despite the fact, mentioned earlier, that in many cases the arithmetic-mean and the median do not fall within the half-metre interval of the geometric-mean, there are groups where coincidence is found (Appendix 10). These latter cases can be very loosely designated as "Normal" or "Gaussian" Distributions. In fig.73, "normal-distribution" of thicknesses is represented by 'N', "abnormal" by 'A', each at the centre-spot of its corresponding group of 100 or 50 dykes. The areas where "normal-distributions" are found are very roughly demarcated. Such areas are largely restricted to the lava-pile, and are close to the axes of dilation in both the lavas and in the pre-Tertiary rocks to the south of and near the Central Complex of Skye. Elsewhere, except on the north coast of Ardnamurchan near the dilation-axis there, the distribution of the thickness of the dykes is "abnormal". Similarities between this and the "normal"/"abnormal" distribution of the trends of the dykes (fig.34) are clear. The significance of these discoveries is discussed in concluding chapters (16:V).

To overcome the problem, that a single contour-map of the average thickness of the dykes does not indicate the frequency-distribution or variation of the thicknesses in any one region, one possible solution is to illustrate the geographical distribution of the regional linear-swarm of dykes falling within certain intervals of thickness. Fig. 74 represents an attempt to accomplish this.

The intervals chosen are (i.) up to 1m., (ii.) between 1 and 2m., (iii.) between 2 and 4m., (iv.) greater than 4m. For each of the 74 groups the value of the percentage-number of dykes within each interval is allocated to its respective

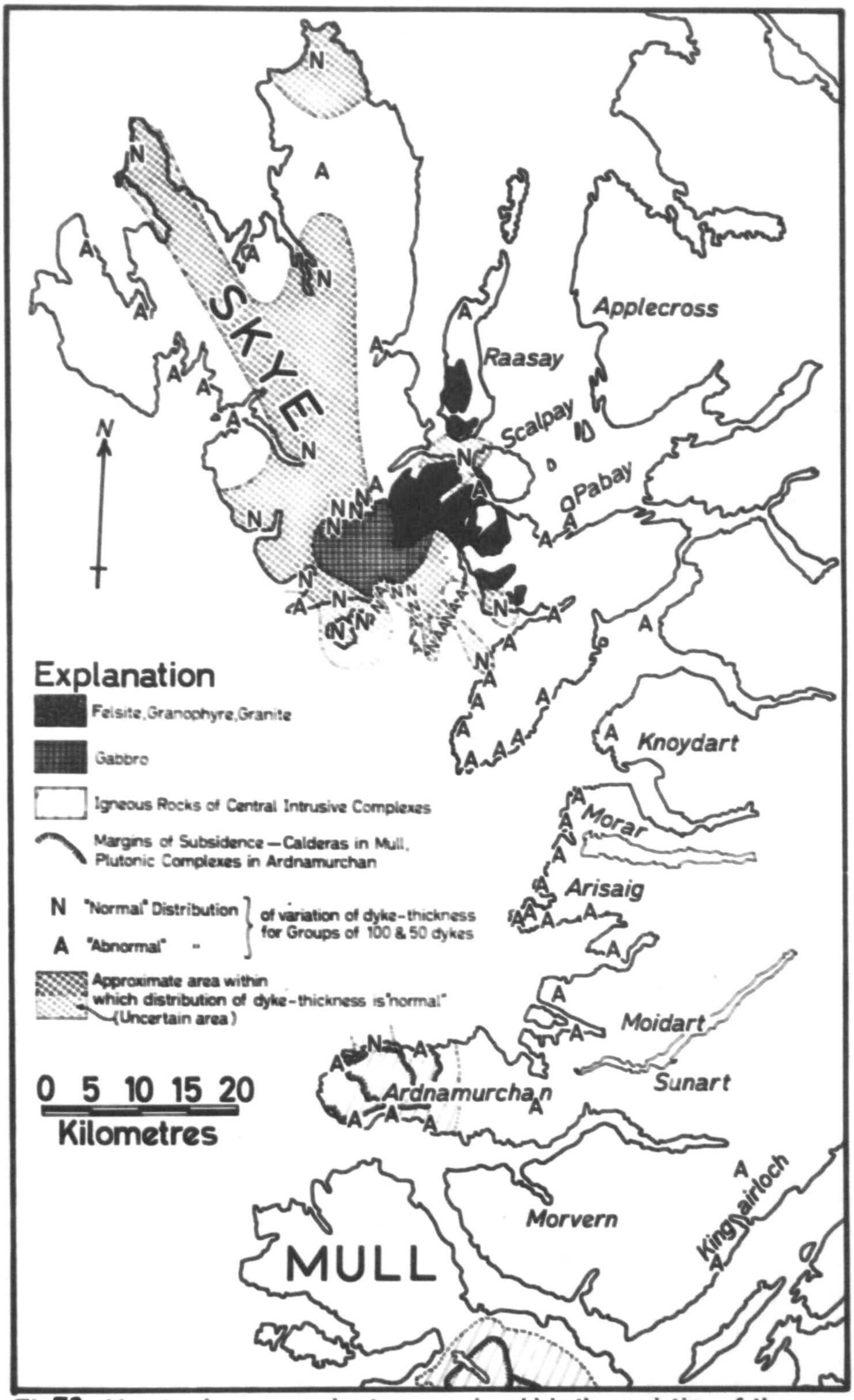


Fig.73. Map to show approximate areas in which the variation of the thicknesses of the dykes approaches that of a Normal (Gaussian) Distribution.

Fig. 74.

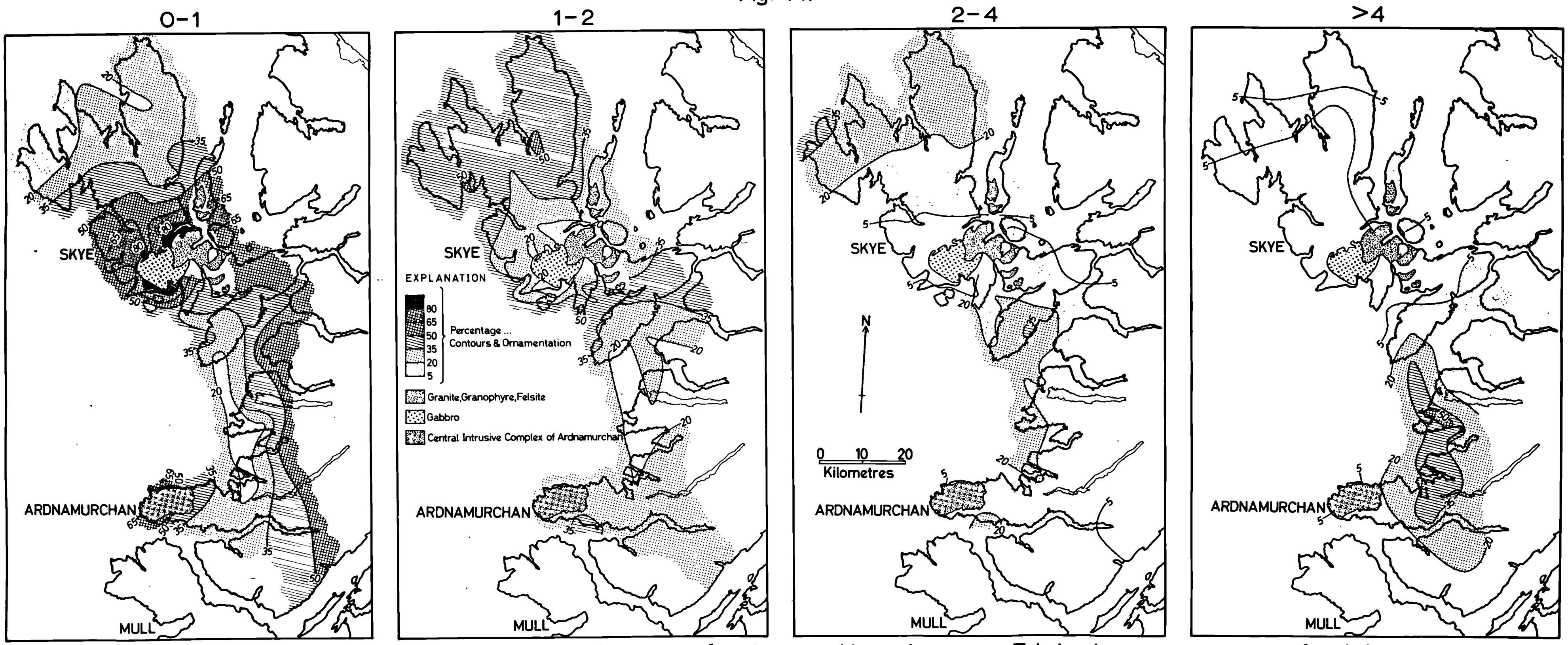


Fig 74 Patterns of the Distribution of the Various Thicknesses of the Dykes

group centre-spot. These values (derived from Appendix 11) are used to construct contour-maps with 5, 20, 35, 50, 65, and 80 per cent. levels. Broader intervals of thickness above 2m. are chosen because of the sparsity of dykes within single metre intervals greater than this value.

The resulting series of four maps illustrates more lucidly than the 74 histograms, though perhaps not as precisely, the geographical distribution of dykes of certain thicknesses. It is not proposed to repeat much of what has already been said about this geographical distribution. Fig. 74 is largely self-explanatory. In combination, the histograms, the variation in the average thickness of the dykes, the geographical plot of the "normal-distributions" of thickness, and the patterns of distribution of various ranges of thickness, constitute a reasonably comprehensive representation of the facts.

To add further to the picture, the frequency-distribution of the thicknesses of those dykes assigned to the Skye-Swarm is represented in fig.75. Again, this is by no means a Gaussian-Distribution, with its pronounced asymmetrical preponderance of dykes of less than 2m. thickness (Appendix 12).

There is some justification for attempting to relate the thicknesses of the dykes, not only to their geographical locality and geological setting, but also to their respective trends. Fig. 76 and the values (for the Skye-Swarm) shown in the right-hand columns of Appendix 13 illustrate this. Of the

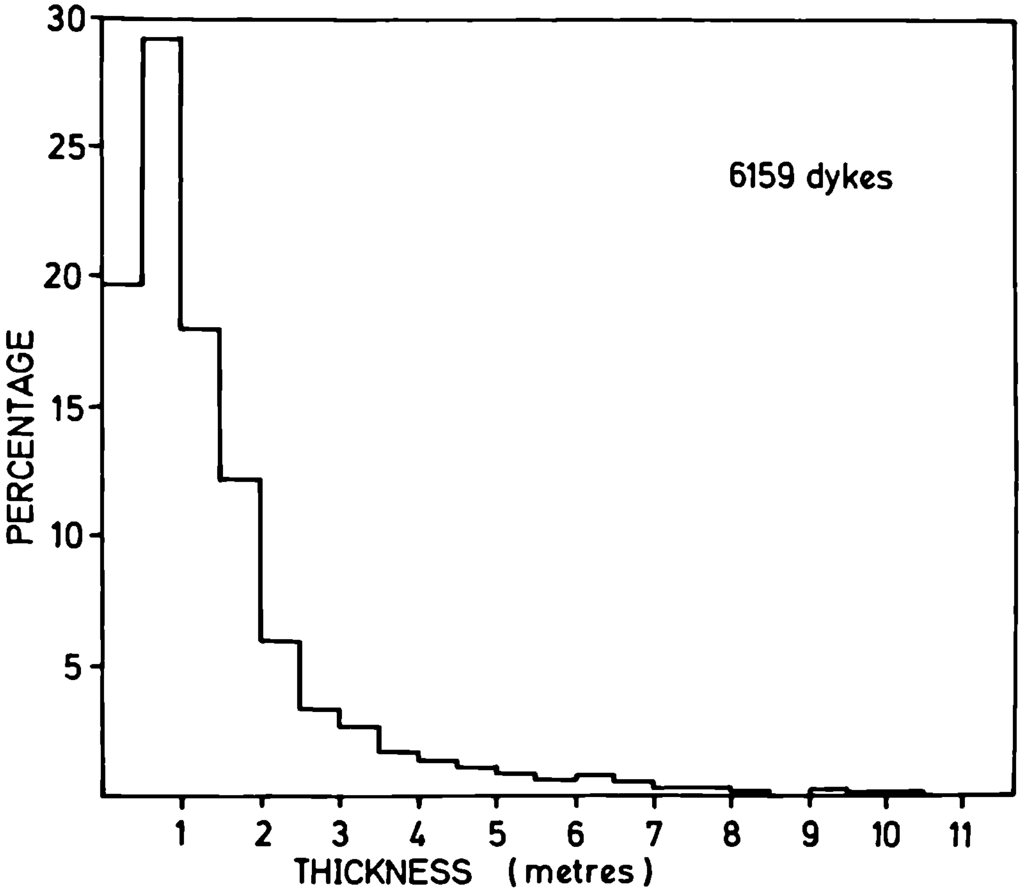


Fig. 75. Frequency - distribution of Thickness for Skye swarm

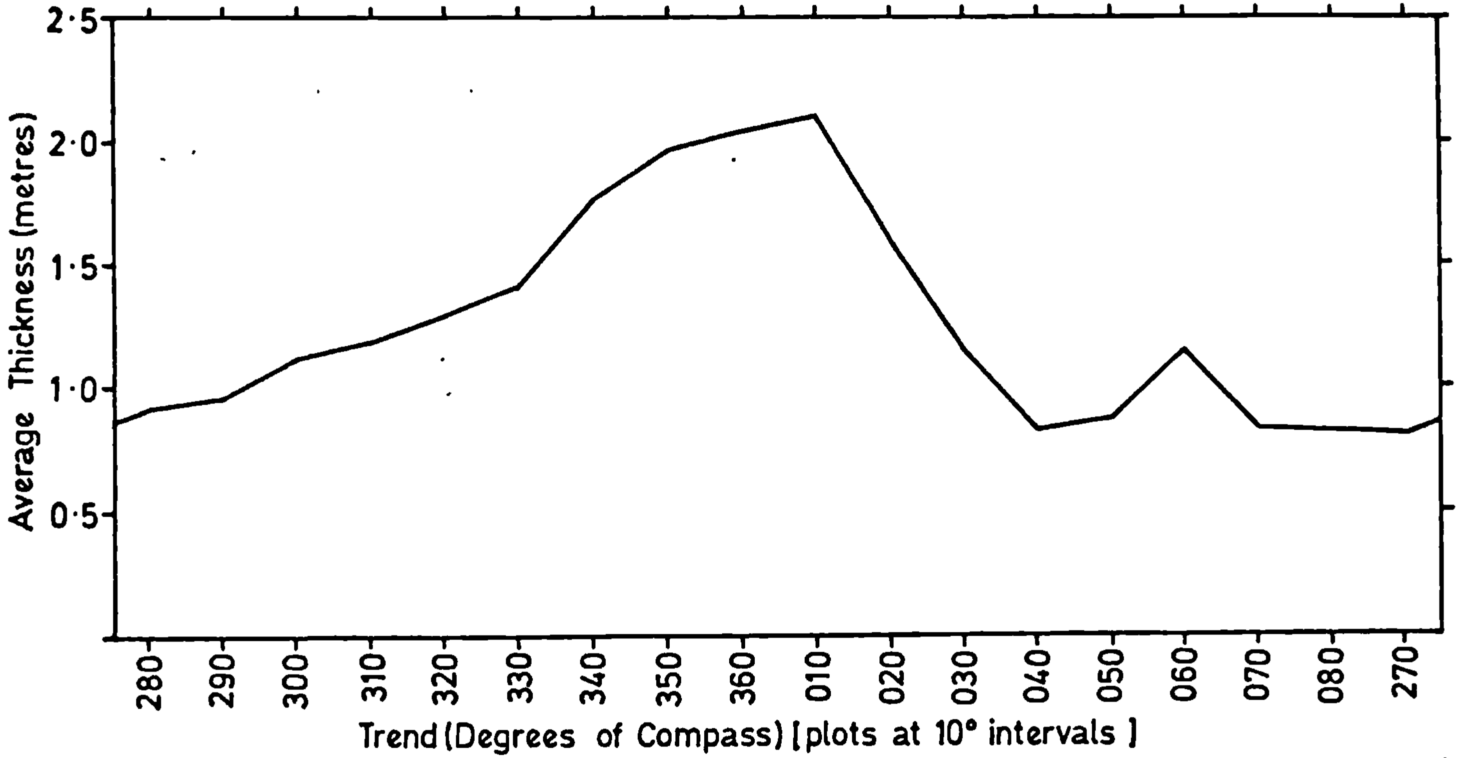


Fig. 76. AVERAGE THICKNESS of DYKES in 10° Intervals of Trend. SKYE-SWARM : 6159 dykes

two choices of intervals, the 10-deg. interval from 275 to 284, 285 to 294, deg., etc., is chosen as the one which best manifests the variations. The greatest average thicknesses are associated with dykes of N.N.W. or N. to S. trends. This is to be expected, since (i.) the average thickness of the dykes increases towards axes which are roughly coincident in position with dilation-axes, at points along which dykes show the least spread of trend from the N.N.W., or from N. to S. as in Morar and Moidart (cf. fig.33 with fig. 48), (ii.) the proportion of narrow dykes is greatest near the Central Complex of Skye, and it is here that dykes of trend other than roughly N.N.W. are found. The correspondence of the graphs of the frequency-distribution of the trends by number of individuals and by summated thickness (fig.16) is also of relevance to the present discussion. It demonstrates that broad dykes do not on the whole possess abnormal trends, i.e. their trends vary little from the average trend for any area.

A density-plot of the trends of the dykes against their respective thicknesses (fig.77; data in Appendix 14) illustrates more fully than fig.76 the relationship of the two functions. Falling within each of the contours of the graph (fig.77) lie the percentage-number of plots as indicated (in intervals of 10 per cent.). The graph is essentially a superimposition of the distribution of the trend upon the distri-

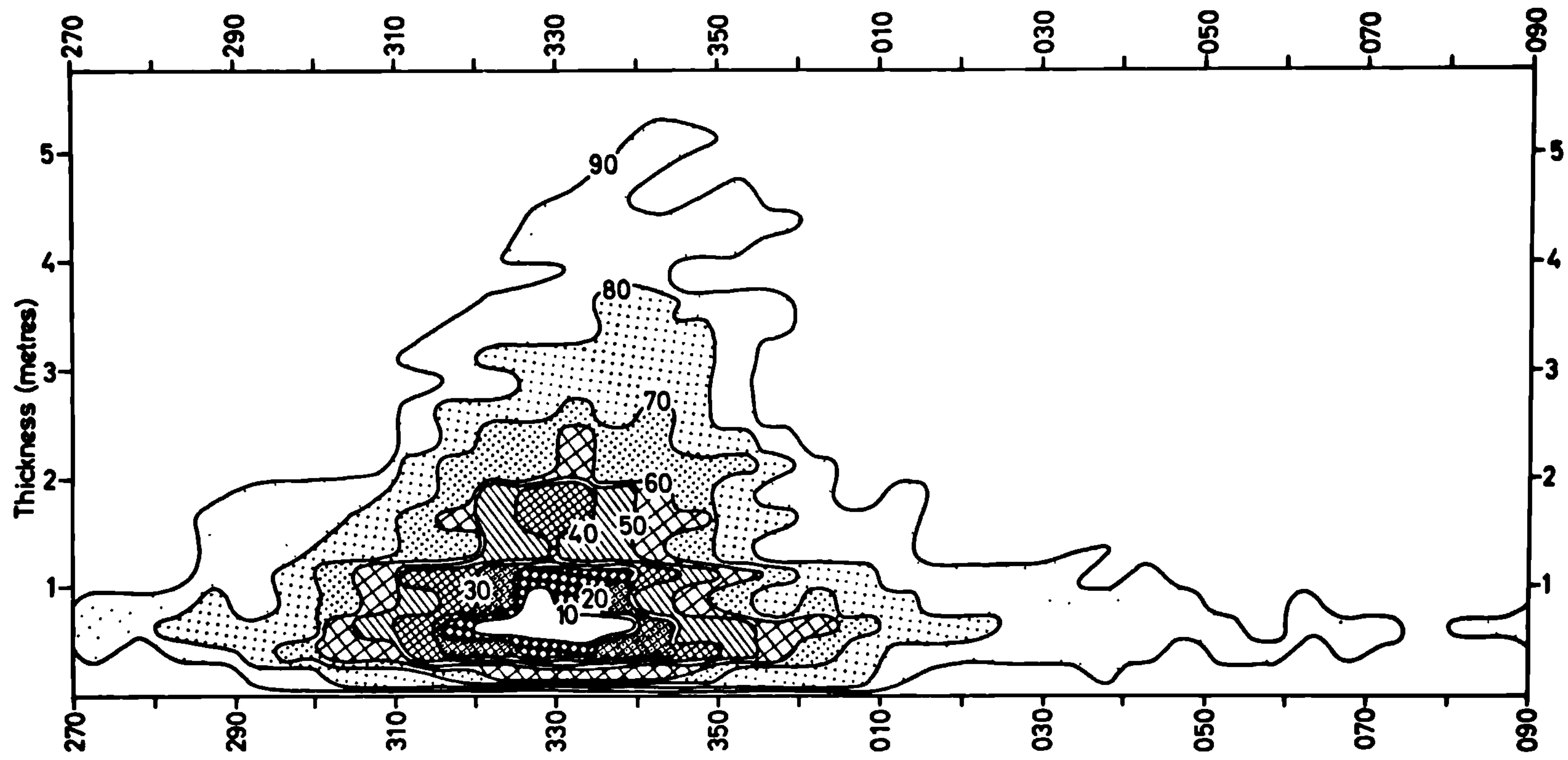


Fig. 77. Dykes of Skye-Swarm... Trend vs. Thickness density-plot

bution of the thickness. The thinner dykes show a wide spread of trend; the thicker dykes exhibit a narrower spread of trend from N.W. through to N. The thicker dykes tend to be of more northerly trend than the majority of thinner dykes. This again reflects the fact that many of the thicker dykes occur in Morar and Moidart, where the average trend is N. to S.

Density-plots of trend vs. thickness of dykes are also plotted for twelve large areas within the single area occupied by the outcrop of the Regional Linear-Swarms of Skye and Ardnamurchan (fig.78). (No corresponding table is given in the Appendices.) Six of these areas correspond to six of the nine areas used in a large-scale analysis of the trend (fig.14). The remaining three areas in the group of nine areas are each divided into two smaller though not equal areas. Thus, Sleat for convenience is divided into north and south, Strathaird into east and west, and the area south and west of the Cuillins into that area south of the Cuillins, including Soay, and an area to the west of the Cuillins. The extent of each of the twelve areas is illustrated by the use of ornamentation. Many of the conclusions to be derived from fig.78, with respect to variations in trend, have already been described (Ch.6:V) but are briefly mentioned again below.

The spreads of trend and thickness in both eastern and

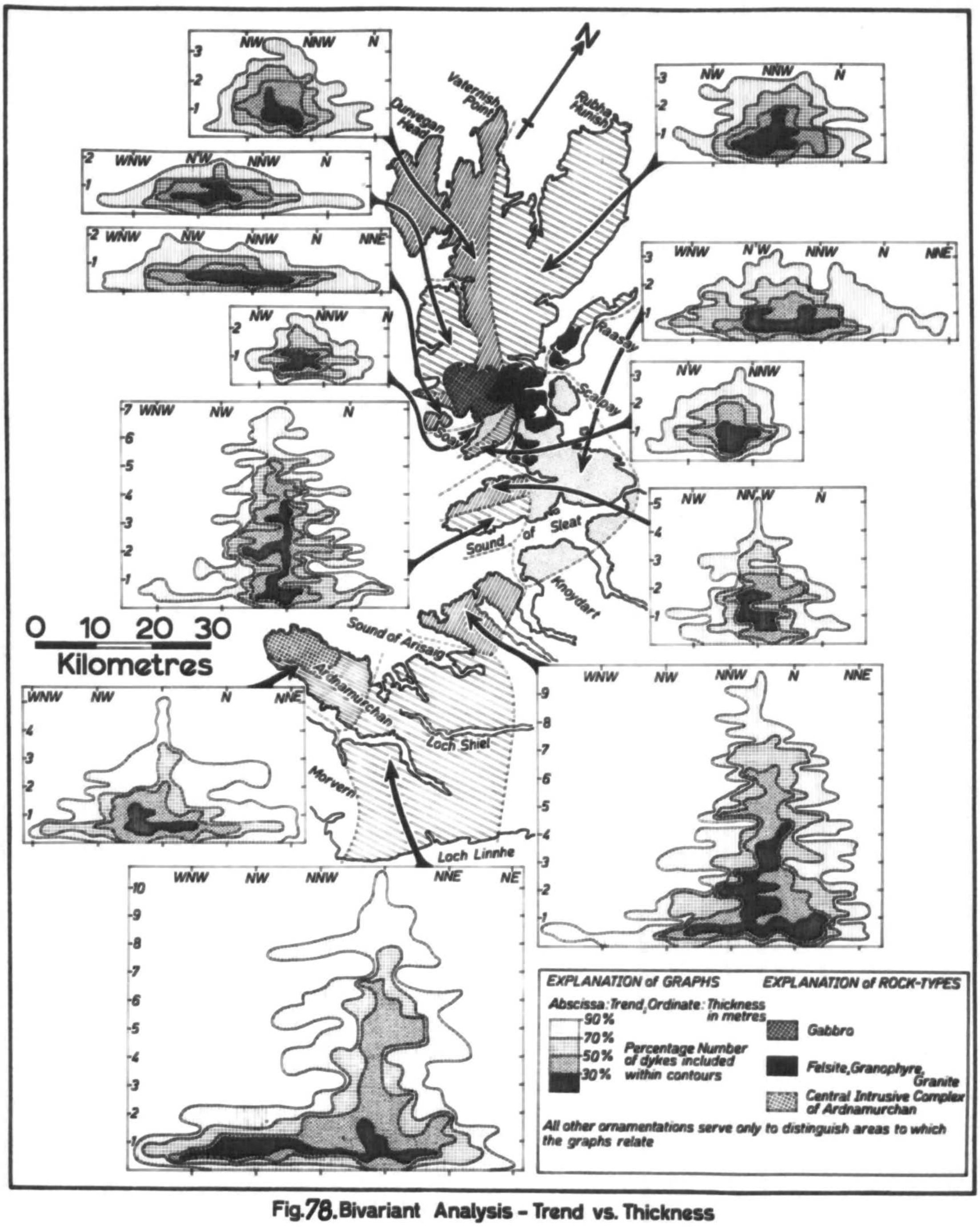


Fig.78. Bivariant Analysis - Trend vs. Thickness

western Strathaird are small, being slightly greater in eastern Strathaird. To the east, in south-east Skye the spread of thicknesses is very much the same, but the spread of the trend is very largely increased. In northern Sleat, the spread of the trend is slightly broader than in eastern Strathaird, and the spread of the thicknesses is increased. This pattern continues to develop progressively through southern Sleat, to Morar, to Moidart and Loch Linnhe, except that in the last district, the proportion of narrower dykes is again increased at the expense of the broader dykes. The swing in trend from Strathaird through to Moidart and Loch Linnhe, from a N.N.W. to a N. to S. predominance, is again evident.

In Ardnamurchan, the density-plot is not typical of a region close-by a Central Intrusive Complex, or at least it does not correspond closely with the same plots near the Central Complex of Skye. The large spread of the trend and thickness in the plot for Ardnamurchan is similar to that found in a region away from the main axes of high-intensity, e.g. south-eastern Skye.

South of the Cuillins and west of the Cuillins, the dykes exhibit a wide spread in trend, and both areas show a narrow spread in thickness. The trends of the dykes in the former area are more north of N.W. than those in the latter. In north-western Skye and north-eastern Skye, similar density-patterns are found, with moderate spreads of thickness and trend. The trends in north-eastern Skye are more north of N.W. than those in north-western Skye, illustrating, once again, the "fanning" of trends across the northern part of the island.

9:III. Thicknesses of Dykes in the Subswarms.

The arithmetic-average thicknesses of dykes of the regional linear N.N.W. swarm in districts around Glenbrittle and northern Scalpay are less than one-metre, rising in parts of the Glenbrittle area to slightly above this value (fig.72). The arithmetic-average thicknesses for dykes of the Glenbrittle and Scalpay N.E. Subswarms are 0.8m. and just less than 1m., respectively (Appendix 15). There is, therefore, little difference in this function whether subswarm or regional linear-swarm is considered. The arithmetic-average thickness of dykes in the Broadford Bay-Applecross Subswarm is 1.2m., which is comparable with the average thicknesses obtained in the N.N.W. linear-swarm in the Broadford Bay and Rubha Suisnish districts (fig.72).

The frequency-distribution of the thicknesses for each of the three subswarms is shown in fig.79 (data in Appendix 15). The histogram for the Glenbrittle-Subswarm is very much like the histograms of groups '18' and '19' (fig.57) which detail dykes of the N.N.W. linear-swarm outcropping in the same district. The histogram for the Scalpay-Subswarm indic-

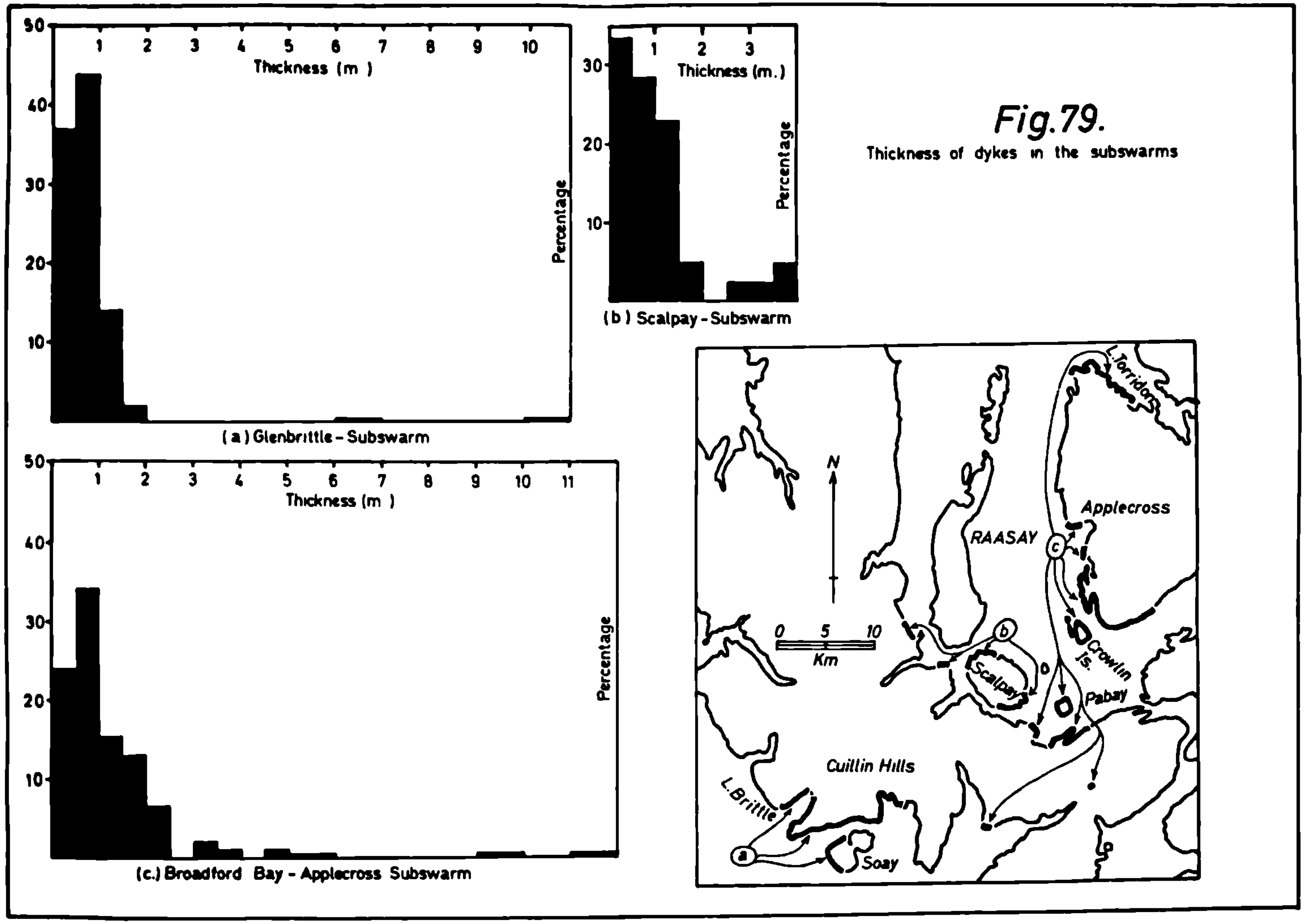


Fig.79.
Thickness of dykes in the subswarms

Fig.79.

ates that there are slightly fewer dykes of less than 1m. breadth in this swarm than in the dykes of the N.N.W. linear-swarm in the same area (fig.56, group '11'). The histogram for the Broadford Bay-Applecross Subswarm shows approximately the same distribution as groups '45' and '46' (fig.61), which represent analyses of the thicknesses of dykes of the N.N.W. linear-swarm in the vicinity of Broadford Bay. The broader dykes in this subswarm outcrop in the Loch Torridon district, at a greater distance from the Central Complex of Skye than most of the other recorded dykes within the subswarm. This segregation of the broader dykes into such localities is again comparable with the behaviour of the dykes of the regional linear-swarm.

Chapter Ten

THE DIPS OF THE DYKES

10:I. Introduction.

The dips of the dykes are registered for reasons similar to those for the recording of their trends. Again, the purpose of the analyses is to discover any patterns in the geographic distribution of the dips, and to interpret the significance of such, both in relation to the controls of the crustal structures and in relation to the other properties of the dykes, e.g. dilation.

The results of the analyses of the dips of the dykes can be used to answer such questions as the following. Do the dykes dip to a focus in a manner similar to that found in cone-sheet complexes? Are the dips of the dykes primary, i.e. original and undisturbed, or are they secondary, i.e. dips imposed by movements in the crust which took place after the consolidation of the dyke? Alternatively, are the dips related to pre-Tertiary fault- and joint-patterns? One aspect of fundamental importance is the relationship between the dips of the dykes and the structure of the lava-pile.

Very seldom have earlier workers attempted to evaluate the significance of the dip of the dykes in swarms throughout the world. Kuno (1964), Wager and Deer (1938), du Toit (1930), and others advanced theories for the origin of the dip of the dykes in the swarm which each studied. Yet statistical or semi-statistical analyses are remarkably uncommon.

Harker (1904,p.305) suggested that the very prevalent dip towards north-east, of the dykes observed by him in Skye, reflects the general dip of the lavas to the west. He concluded that the dykes were intruded vertically, and that those which dip were injected before that movement which Harker envisaged to have caused a tilting of Skye towards the west. He excluded the case of multiple-intrusions, where a second dyke, intruded post-tilting, "would tend to follow the guidance of an earlier one, even when that involved some departure from the vertical direction".

10:II. Measurement and Analysis of the Dips of the Dykes.

Similar problems, to those met in the measurement of the trend and the thickness of the dykes, are encountered in the assessment of their dips. Accurate observation of the dip is restricted by lack of exposure. Dykes exposed in 20 or more metres of cliff-section are often seen to possess a highly sinuous dip. In some cases the sinuosity is regular, and a reasonable average value is ascertainable. Whether the variation of the dip in the vertical is regular or not is indeterminate, however, when the amount of exposure in that direction is minimal. As in the case of trend, appeal must be made to the "law of averages", that one error in the measurement of the dip is counterpoised by another (in the same group-analysis) of the opposite sense.

Because of the problems outlined above, dip is only quoted to the nearest 5deg. In some cases the error is even greater; and in rare cases it is very much less. The unfortunate result is that in a bivariant analysis (trend vs. dip) the plots of the poles normal to the margins of a number of dykes fall on distinct arcs separated by 5deg. intervals. It seems preferable, in consequence of this, to illustrate the variation of the dips of the dykes by means of histograms. A value of dip of 75deg. implies that the true dip of the dyke lies between 75 and 79, inclusive, deg., etc. An added advantage of the use of simple histograms, as opposed to plots of the poles normal to the dyke-margins, is that dip is analysed as a single function, largely independent of trend.

Figs. 80 to 95 are a succession of dip-histograms for the 74 groups of 100 or 50 dykes, each brought to a percentage basis. Dykes are shown as vertical (central, unshaded portion), or with dips to the south-west or north-east. This method of representation is attended by certain problems which are now discussed.

The trend of a dyke is normally quoted within the 180 deg. range passing from 270-deg., through north, to 90-deg. of compass. The dip of a dyke of trend 315-deg. of compass is either towards N.E. or S.W. The dip of a dyke of trend

20-deg. of compass is either at 290- Or 110-deg. of compass. By analogy with a N.W.-trending dyke, it can be said of this second case that 290-deg. is anti-clockwise of 20-deg. (hence "S.W."), and 110-deg. is clockwise of 20-deg. (hence "N.E."). Consider, however, the cases of two dykes trending at (i.) 280-deg., and (ii.) 80-deg. of compass. Suppose that the first dips towards 10-deg. of compass (clockwise — hence, by analogy, "N.E."). Suppose that the second dips towards 350-deg. of compass (anti-clockwise — hence, by analogy, "S.W."). And yet, the direction of dip of one of these two dykes is within 20-deg. of that of the other.

It is fortunate that the vast majority of the trends fall within the north-west quadrant, and that this problem does not then arise. However, for trends lying in the north-east quadrant, the corresponding dips fall within the south-east or north-west quadrants. Despite the anomalies which arise, the former are classed along with dykes dipping to the north-east, and the latter with dykes dipping to the south-west. Plots of the poles normal to the dyke-margins would obviously preclude these anomalies, but because such plots are complicated by inclusion of the precisetrend, the decision is not to employ them.

Only a brief description of figs. 80 to 95 is deemed necessary, since the histograms are largely self-explanatory. As with the corresponding group-analyses in Chapters Six (V) and Nine (II), the group-analyses of the dip (Appendix 16) represent a detailed and comprehensive account of the behaviour of this function.

It is notable that within the 74 groups a total of 19 dykes dip at less than 45-deg. For normal purposes of definition, it would be convenient to draw a distinction between dykes and sheets using this angle of dip as a dividing line. However, in certain exceptional cases there is little doubt that these more shallow-dipping tabular bodies are dykes (Ch.4:II). These particular dykes outcrop in southern and south-eastern Skye, and on the mainland between Arisaig and Loch Linnhe. On Skye, these low dips are in all cases towards N.E., as are the dips of the majority of dykes in the southern part of the island. These dips are generally irregular, varying from vertical to almost horizontal, and the recorded angle is merely an average value of dip for these highly discordant bodies. On the mainland, the exceptionally low dips are recorded for bodies which lie parallel to the foliation planes or joints of the Moinian rocks, and in this respect are analogous with many of the more steeply-dipping undoubted dykes.

Vertical dykes in the groups of northern Skye and Raasay (figs. 80 and 81) account for about 30 per cent. of the total, with their proportions more markedly increased

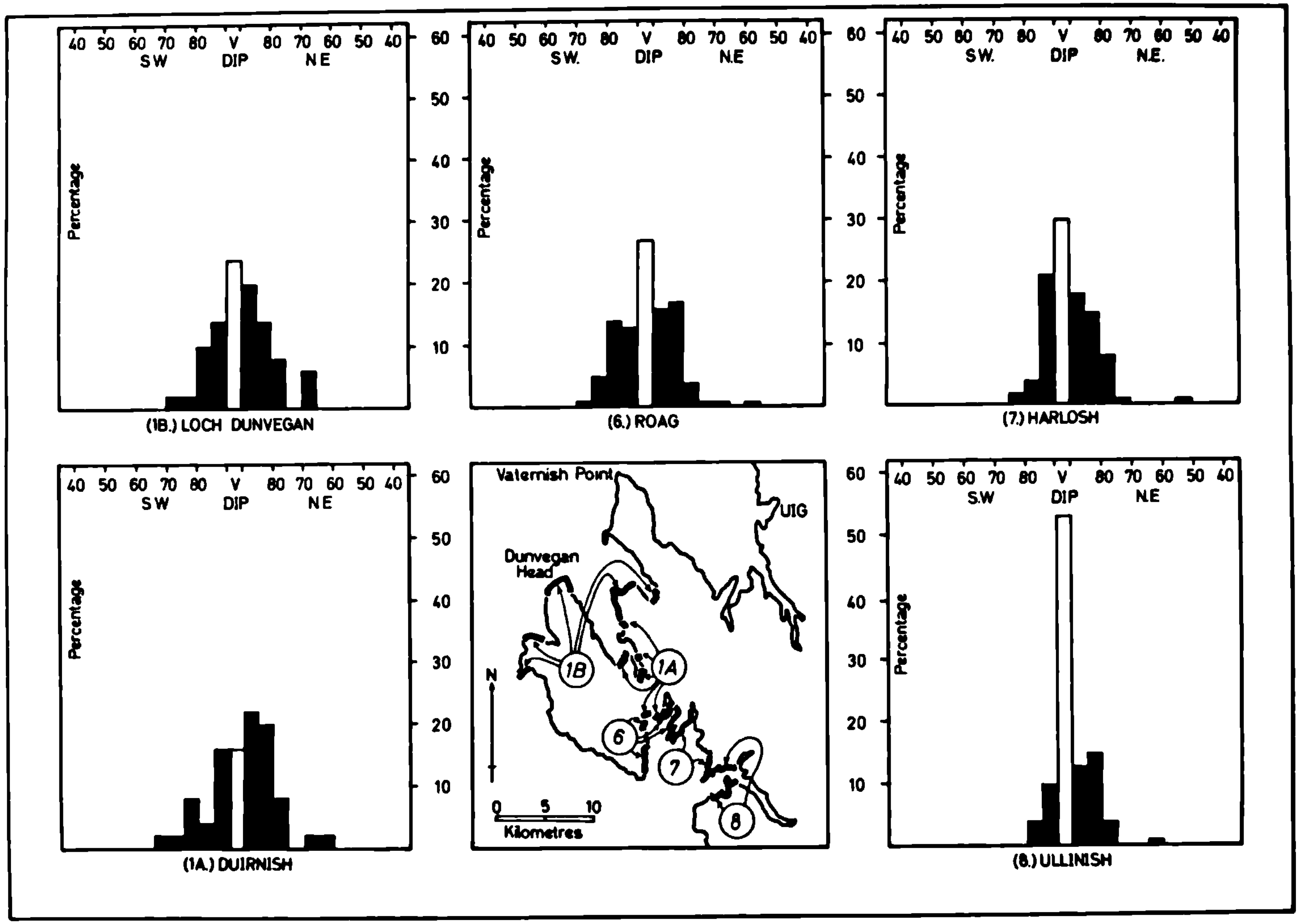


Fig.80. Dip-analysis

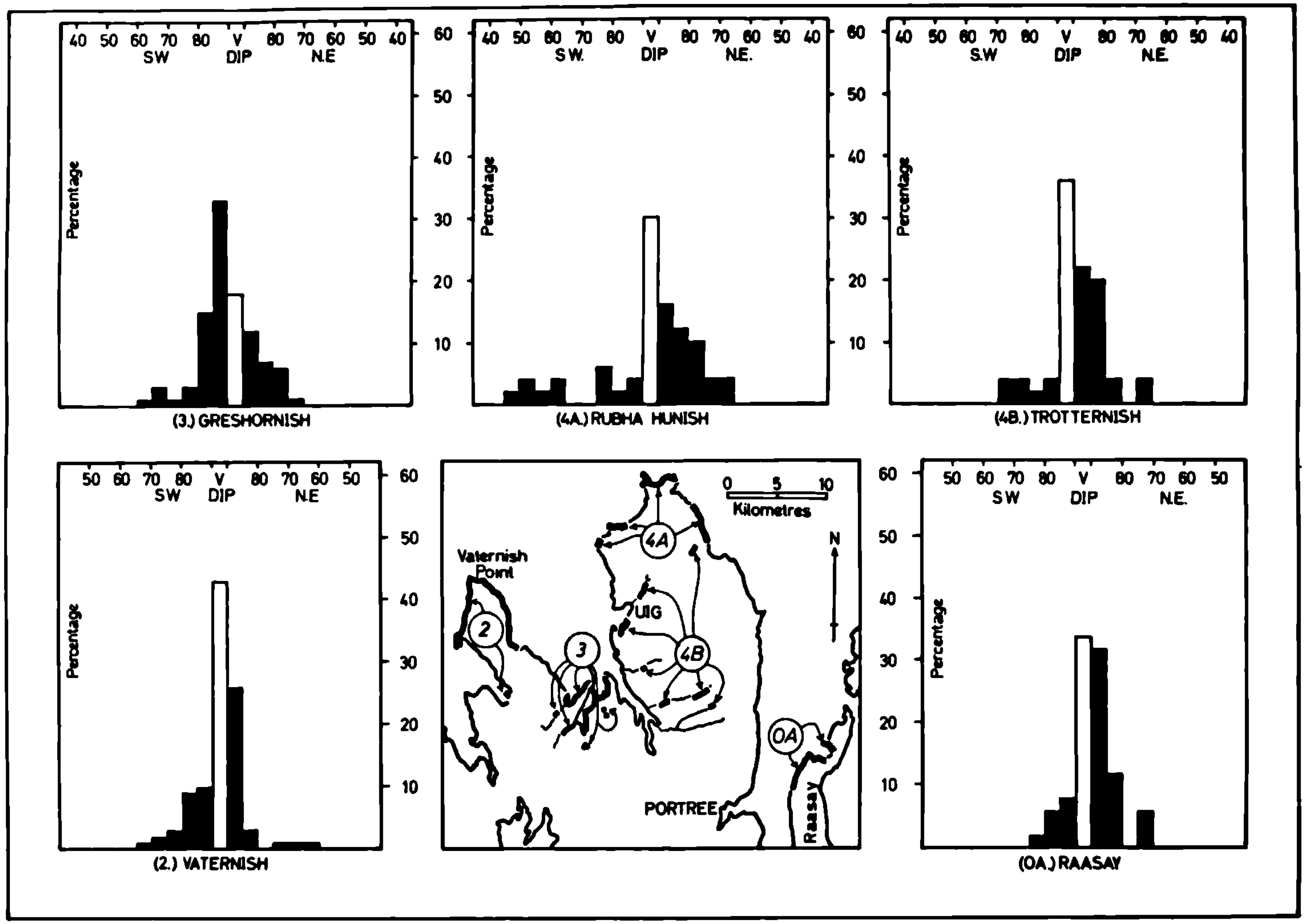


Fig.81. Dip-analysis

in groups '8' and '2', close to the locations of the dilation-axes. The dips either side of vertical, in groups of figs. 80 and 81, are approximately equally apportioned, and range, with a few exceptions, mostly upwards of 70-deg. Some analyses designed to illustrate the relationships of the dips of the dykes to their position with respect to the dilation-axes are given later in this chapter.

In the west-central areas of the lava-pile (fig.82) the proportion of vertically-inclined dykes is greater, especially in groups, '13', '14', '15', near to the Central Intrusive Complex. Dykes dipping either side of vertical are roughly of the same numbers again. Except for '11', groups depicted in fig.83, show a preponderance of dips towards N.E., and a paucity of dips towards S.W. The proportion of vertical dykes in the groups of fig.83, which groups are farther removed from the dilation-axes than those of fig.82, is again relatively low.

Conversely, groups shown in fig.84 show a dominance of dips towards S.W., with a paucity of dips towards N.E. The numbers of vertical dykes range between 30 and 40 per cent.

Fig.85 portrays groups with fairly equal distributions of dips either side of vertical, and with little range less than 70-deg. Group '25' is somewhat anomalous in comparison to others of fig.85, in that the proportion of vertical

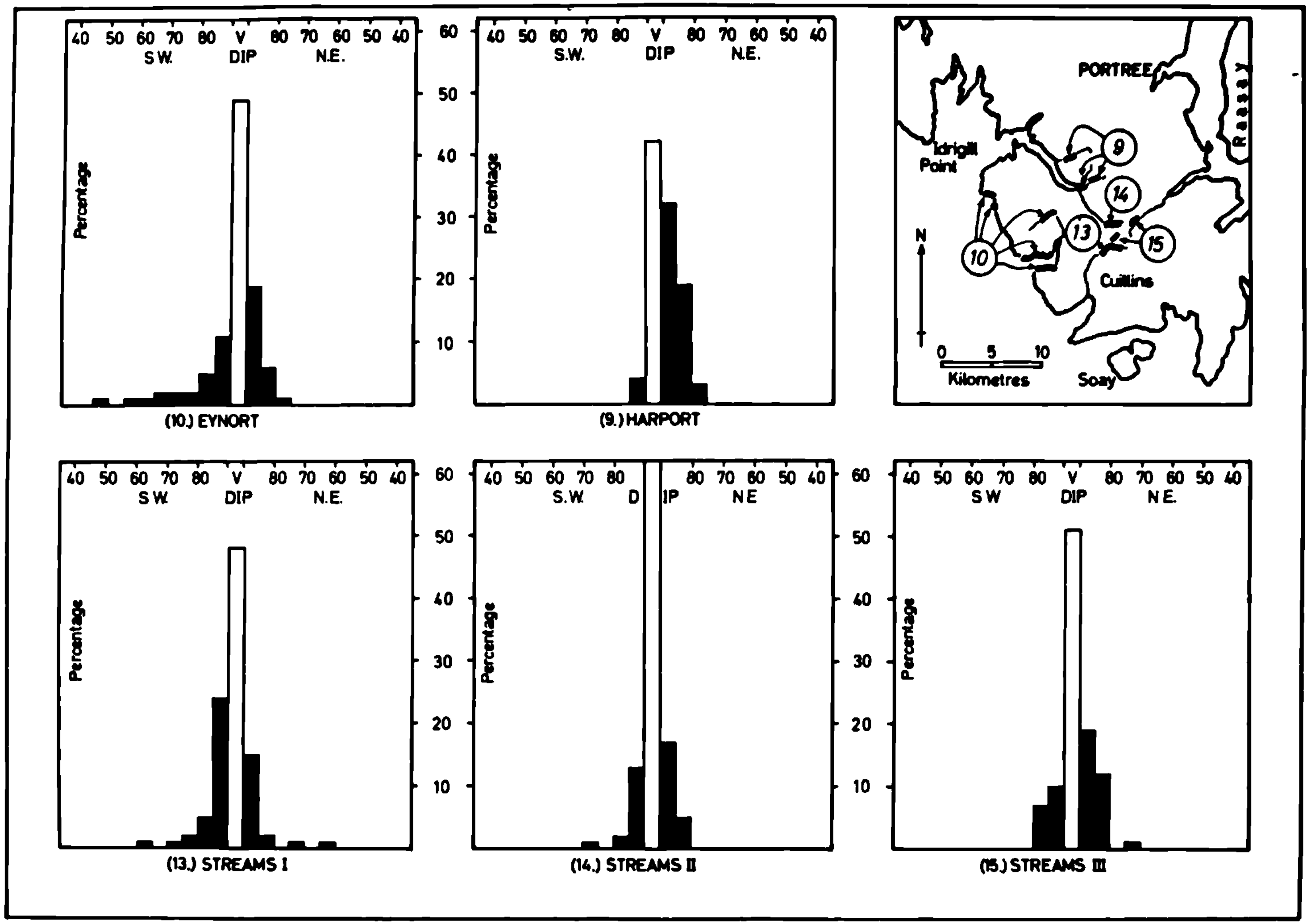


Fig.82. Dip-analysis

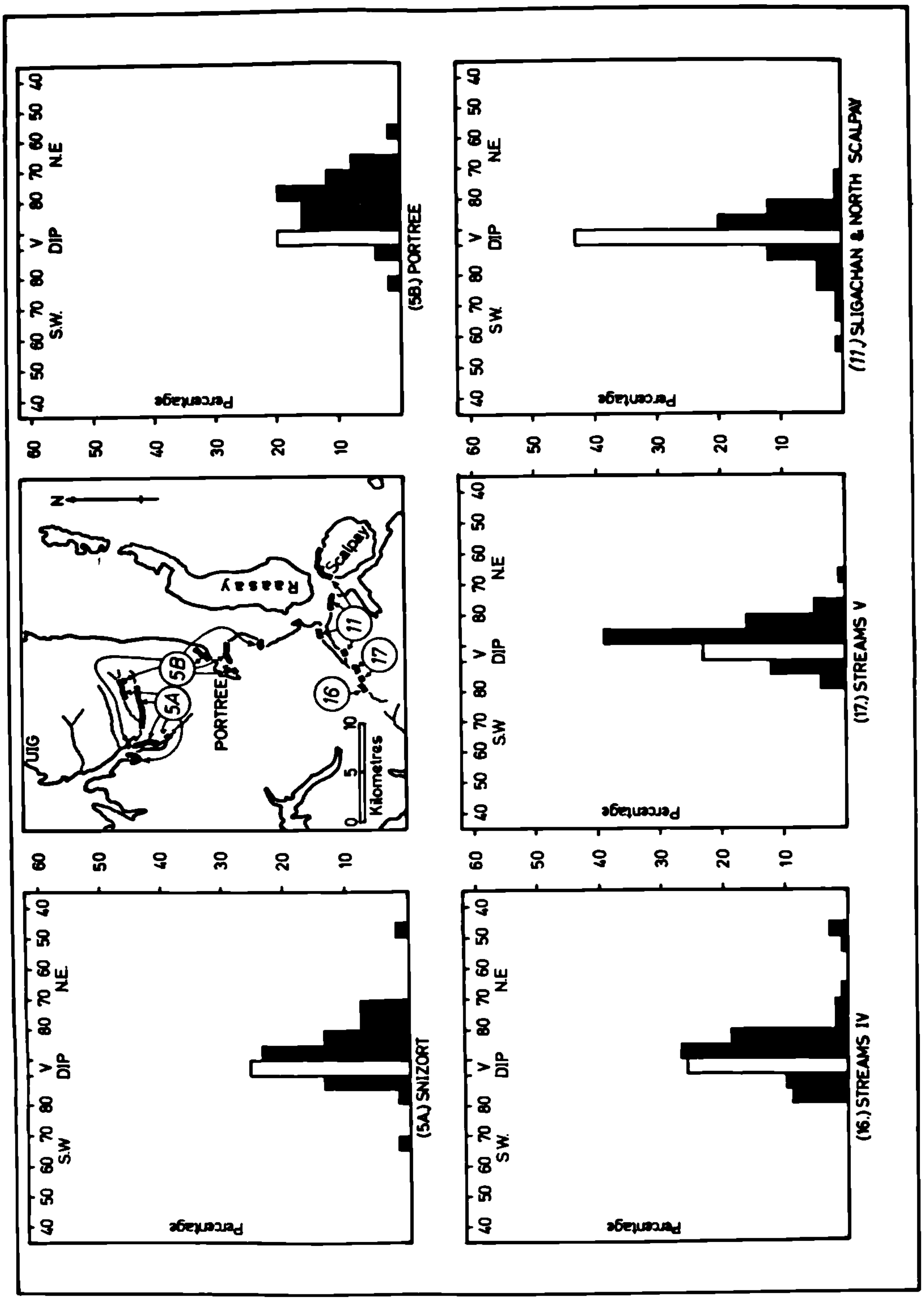


Fig.83. Dip-analysis

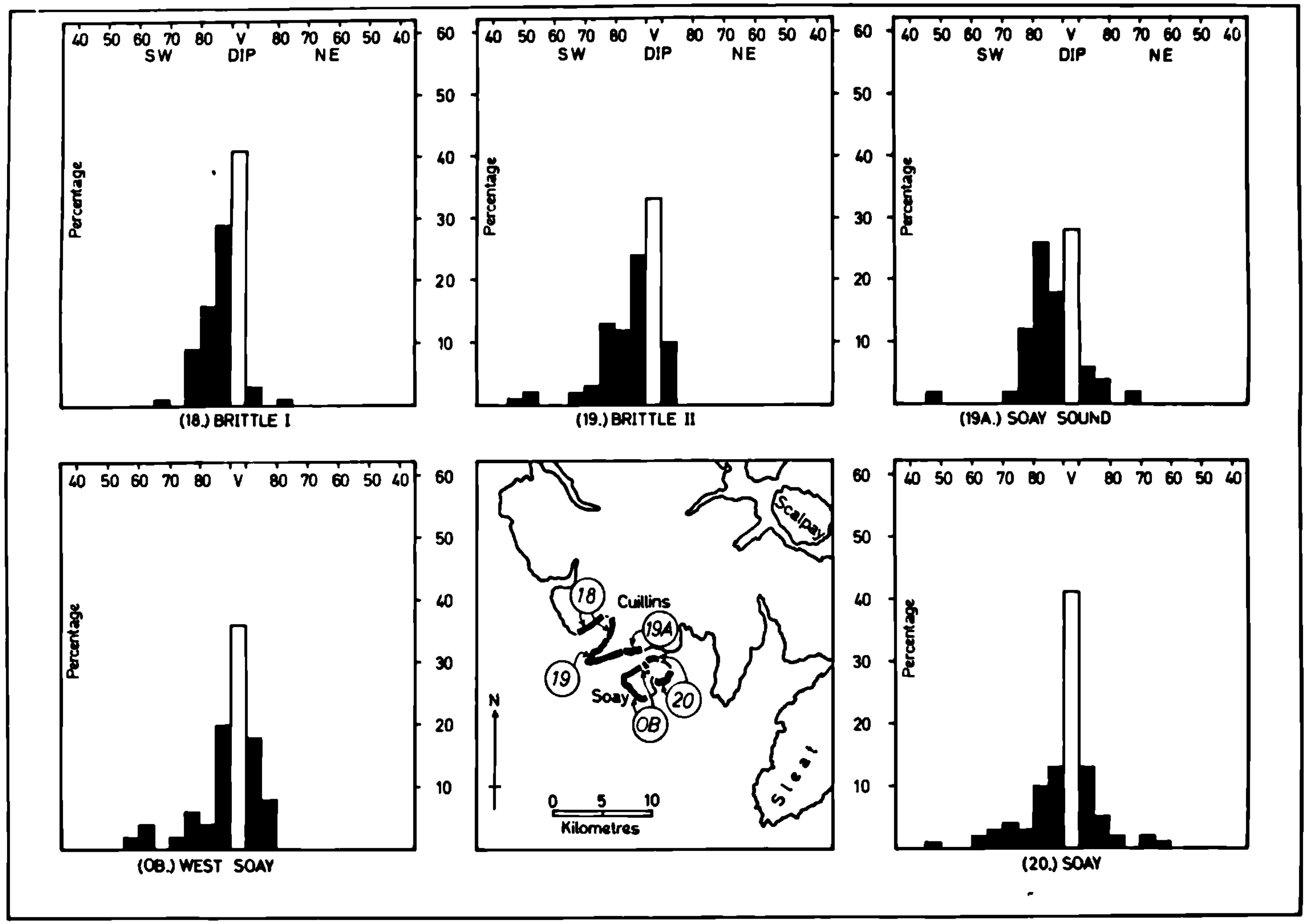


Fig. 84. Dip-analysis

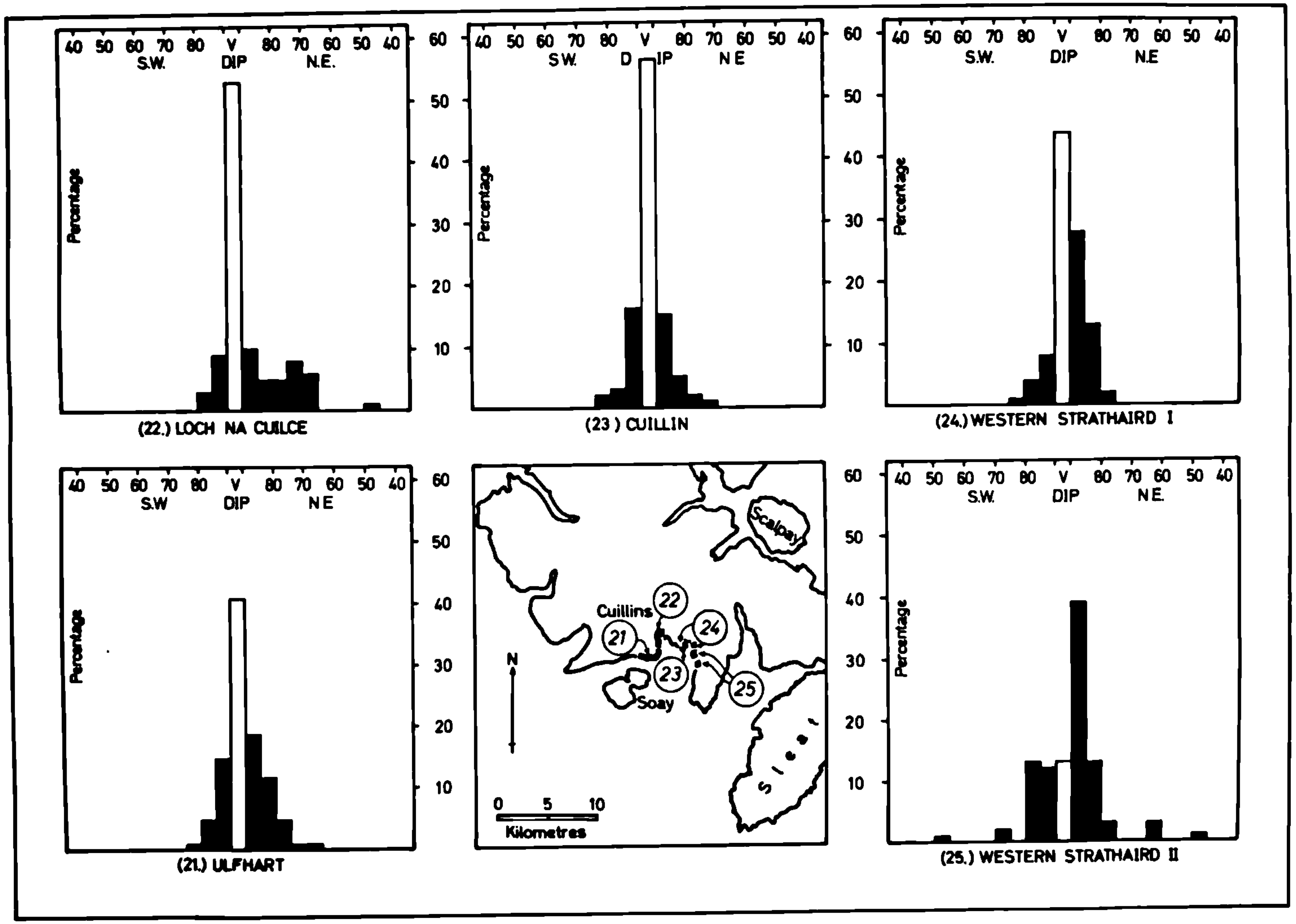


Fig.85. Dip-analysis

dykes is very much lower, and the spread of dips is very much greater.

Figs. 86 and 87, comprising groups covering much of Strathaird, illustrate dip-distributions of variable character, excepting their equally moderate development of vertical dykes. Groups '26' and '28' are comparable in their broad spread and symmetry about the vertical. The remainder of the groups show a tendency for prevalence of dips towards N.E. over dips towards S.W.

Groups '12', '45' and '46' (fig.88) exhibit a very broad spread of dip, almost equally-developed on either side of vertical. Vertical dykes are especially prominent in the first two of these groups. Groups '34' and '35', which lie nearer to the main axis of dilation, show a dominance, especially in '34', of dykes dipping towards N.E.

The groups of northern Sleat (fig.89) display a very marked abundance of dykes dipping towards N.E. Proportions of vertical dykes average at about 30 per cent. The groups of southern Sleat (fig.90) show a much broader spread of dips, with an equal distribution on either side of vertical in group '44', and in the Glenelg group, 'OC'. Elsewhere the preponderance of N.E.-dipping dykes in southern Sleat is very evident.

The groups on the mainland (figs 91 to 93) do not continue to develop the tendency shown by groups from Strath-

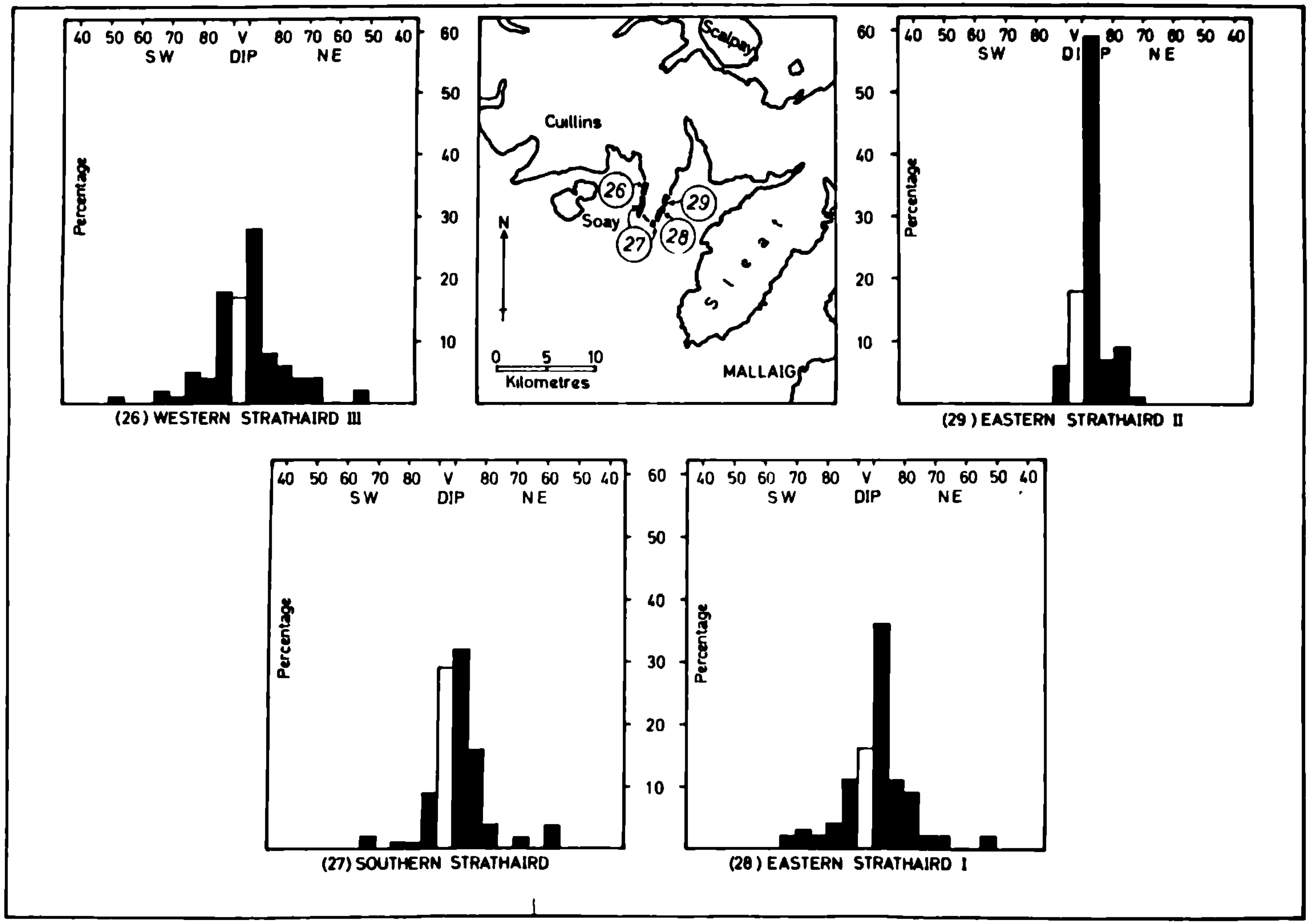


Fig. 86. Dip-analysis

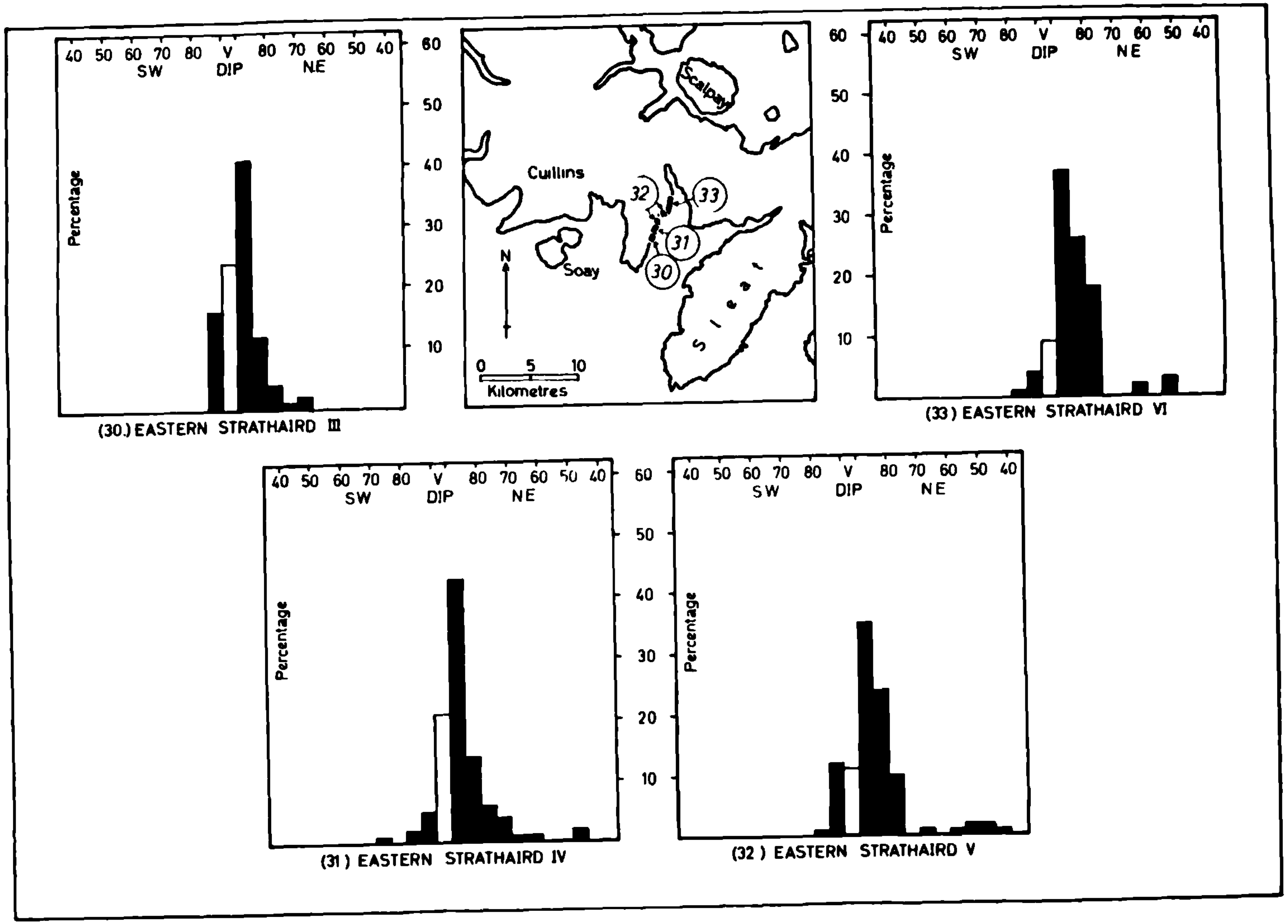


Fig.87. Dip-analysis

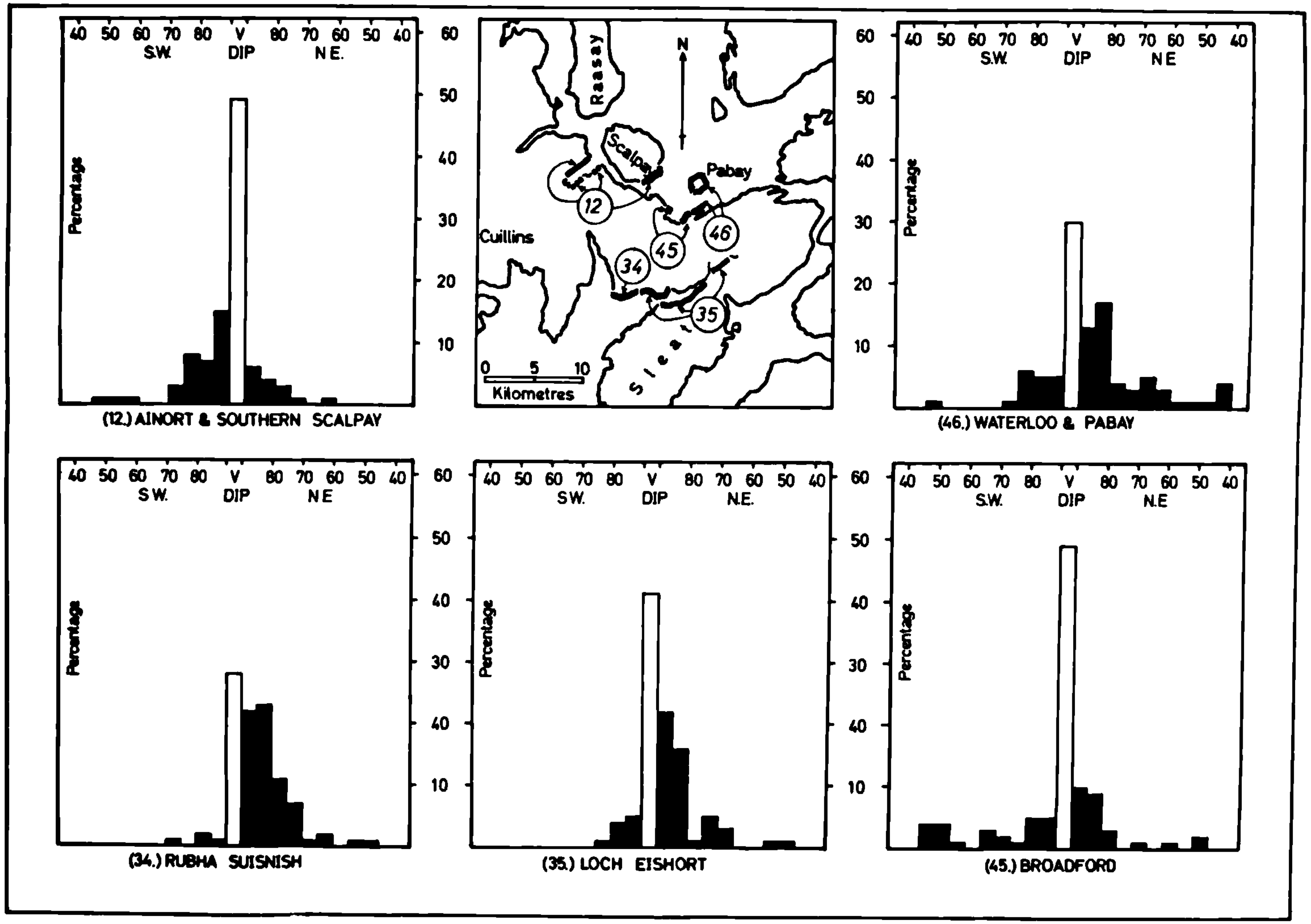


Fig. 88. Dip-analysis

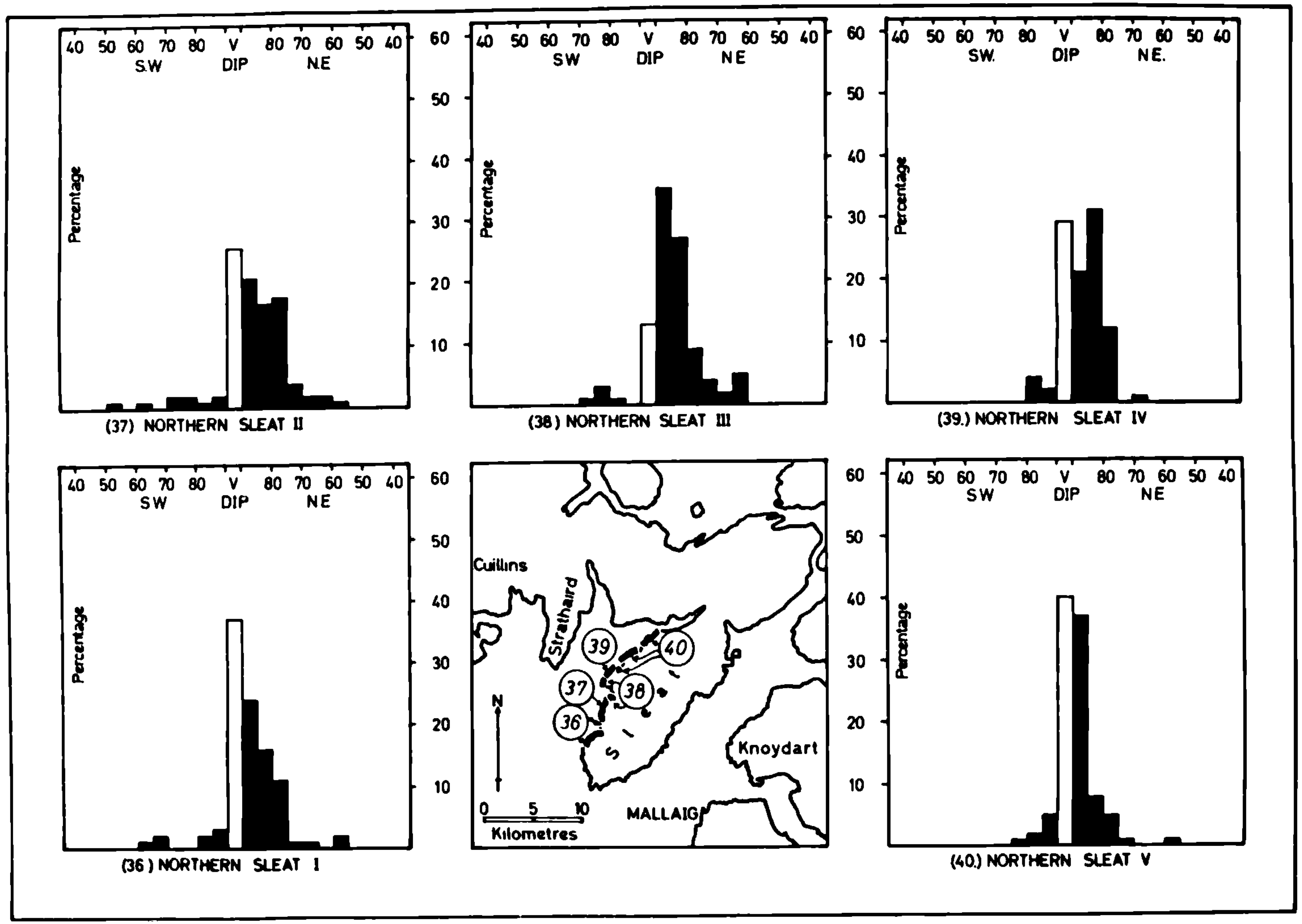


Fig. 89. Dip-analysis

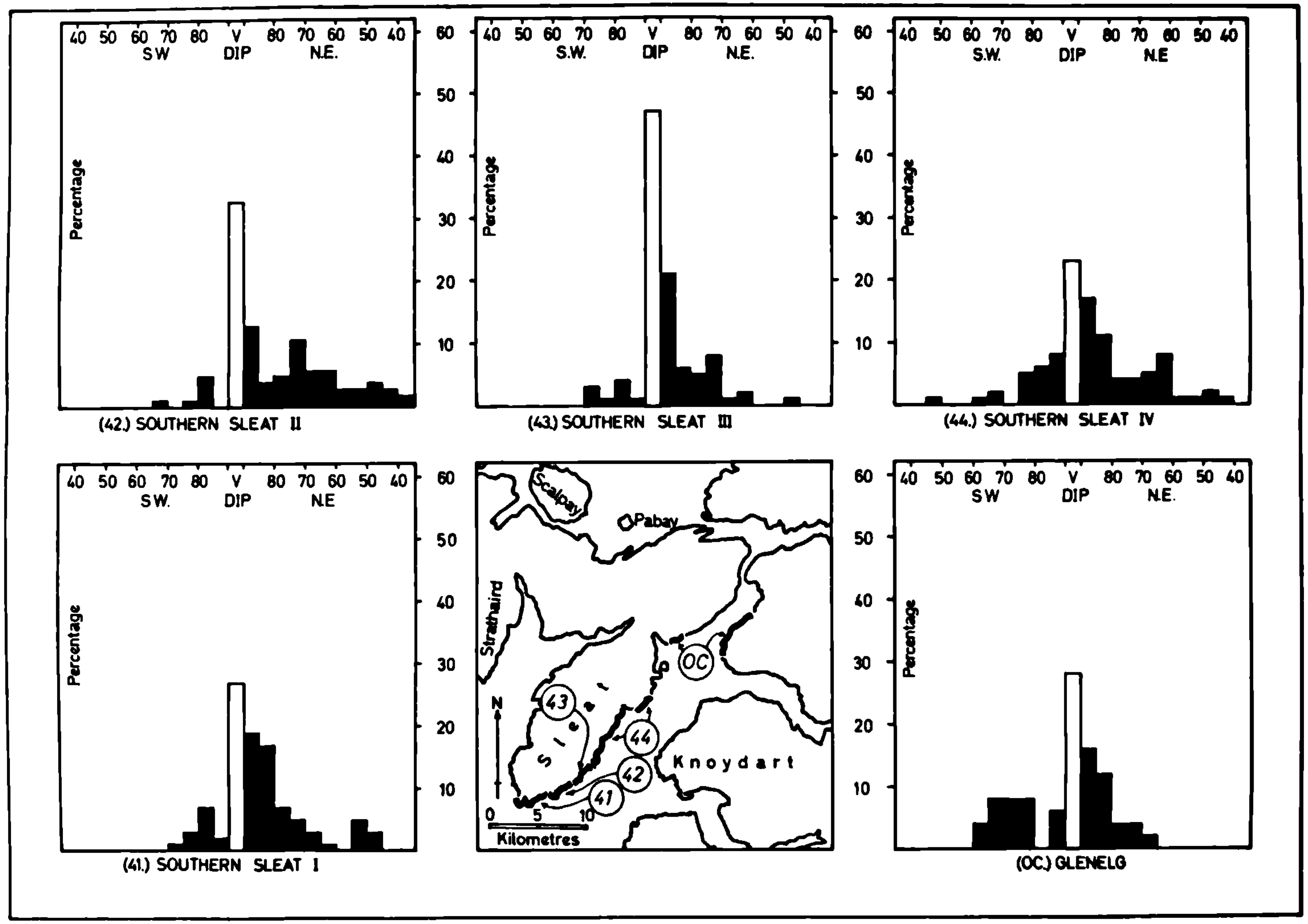


Fig.90. Dip-analysis

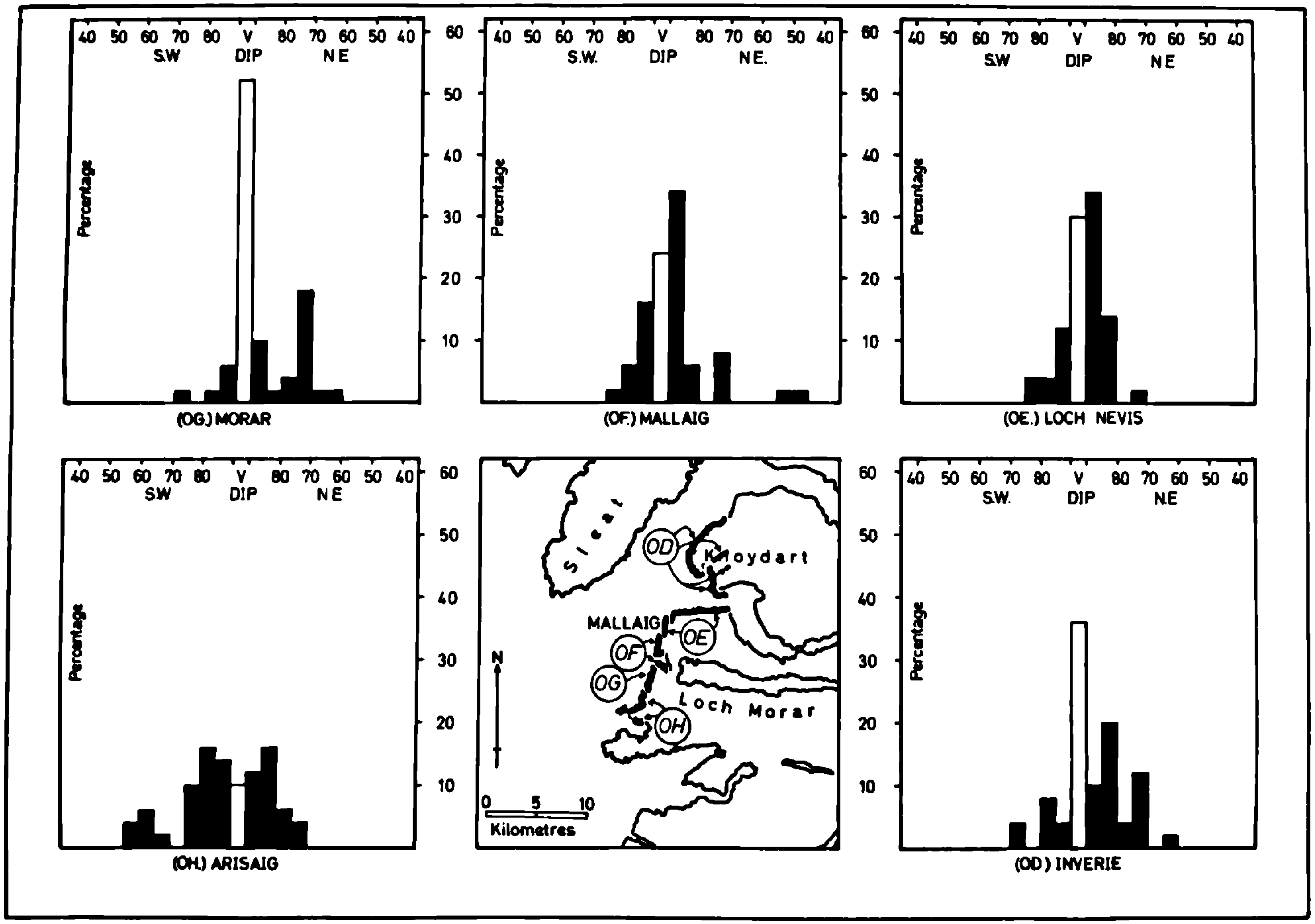


Fig.91. Dip-analysis

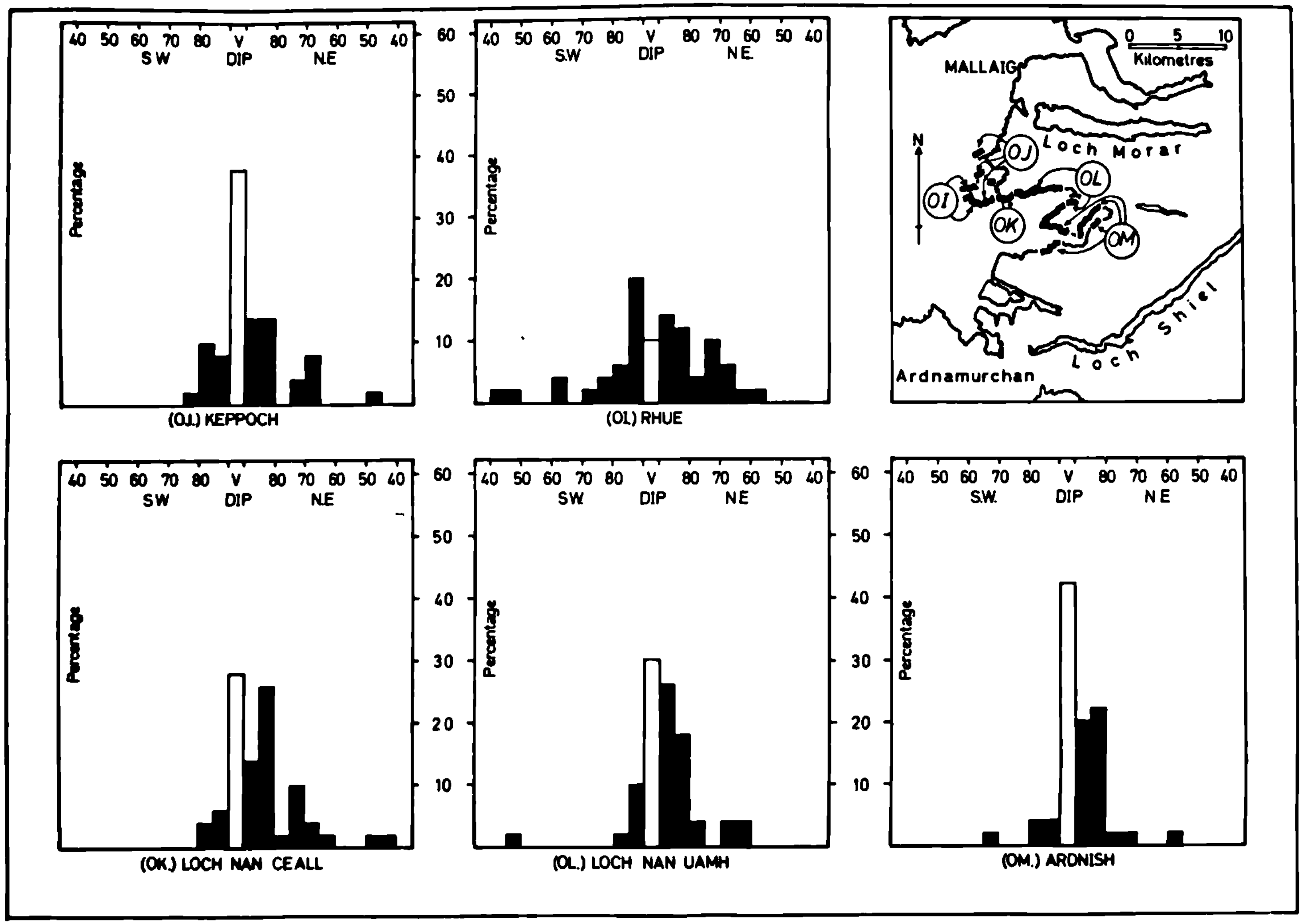


Fig. 92. Dip-analysis

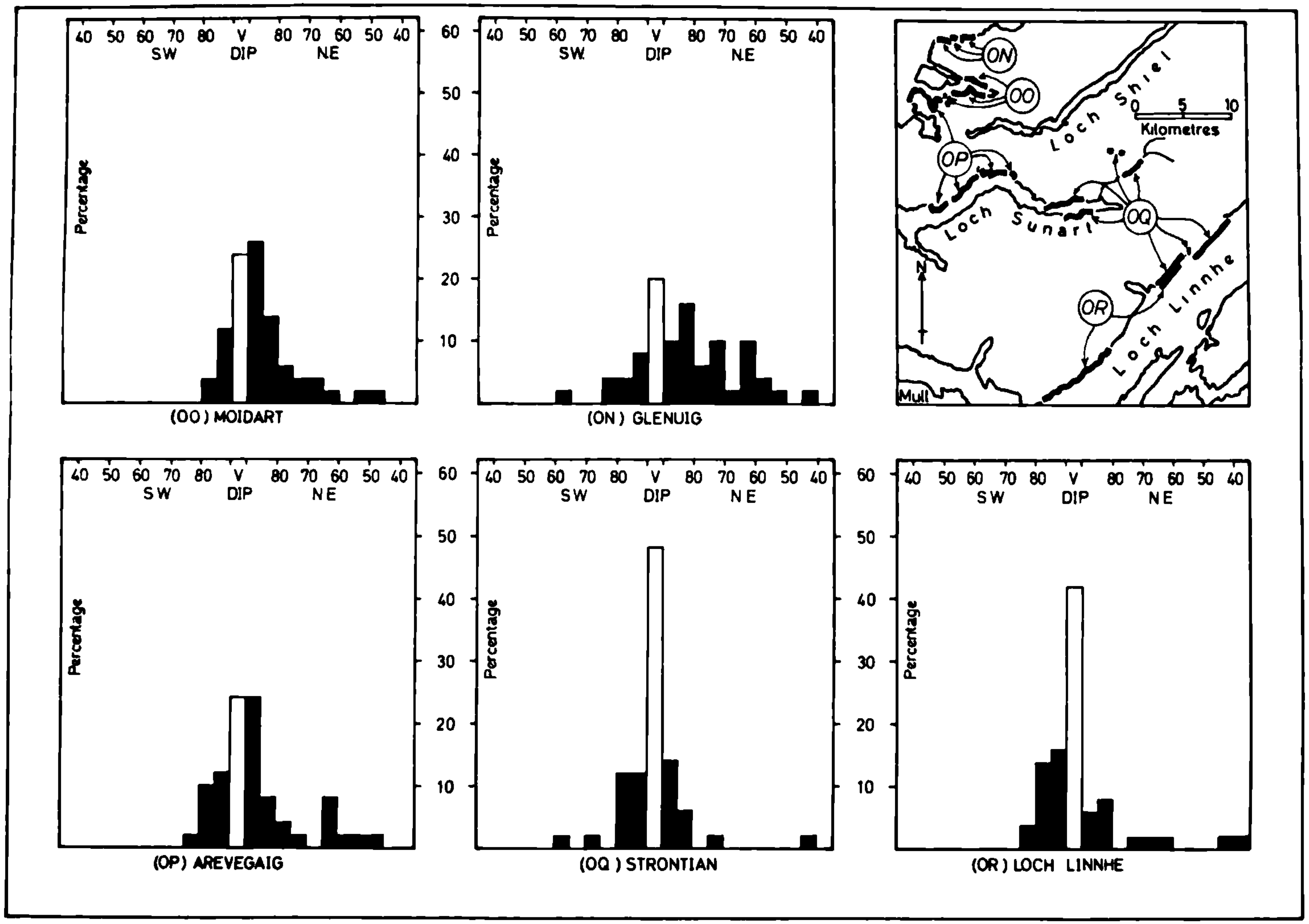


Fig.93. Dip-analysis

aird, through northern to southern Sleat, for increasing proportions of dykes dipping towards N.E. In certain cases, however, this predominance of N.E.- over S.W.-dipping dykes is found, e.g. groups 'OK', 'OL', 'OM' (fig.92), and groups 'OO', 'ON' (fig.93). In other cases, the spread is broad and evenly-distributed on either side of vertical, e.g. 'OH' (fig.91), and 'OJ', 'OI' (fig.92). In yet other cases, the dip-distribution is very irregular, with moderately low-, N.E.-dipping dykes gaining dominance, i.e. in groups 'OD', 'OG' (fig.91). In the remaining four groups — 'OE', 'OF' (fig.91), and 'OQ', 'OR' (fig.93) — the dips to either side of vertical are fairly equal in proportion, with a slight bias towards N.E. dips, some of which are of low-angle.

The inclination of seventeen dykes on parts of the south-east coast of Harris is steep, with no preferred direction of dip.

Certain groups in Ardnamurchan (figs 94 & 95) have numerous dykes of vertical-inclination, e.g. 'AD', 'AC' (fig.94), and 'AE' (fig.95). In groups 'AC' and 'AD' the spread of the dips is narrow, compared with the remaining four groups in Ardnamurchan. The spread is especially marked in groups 'AB' and 'AG', in the eastern part of the Peninsula, far-removed from the localities of the main dilation-axis of the Ardnamurchan-Swarm. There is a certain

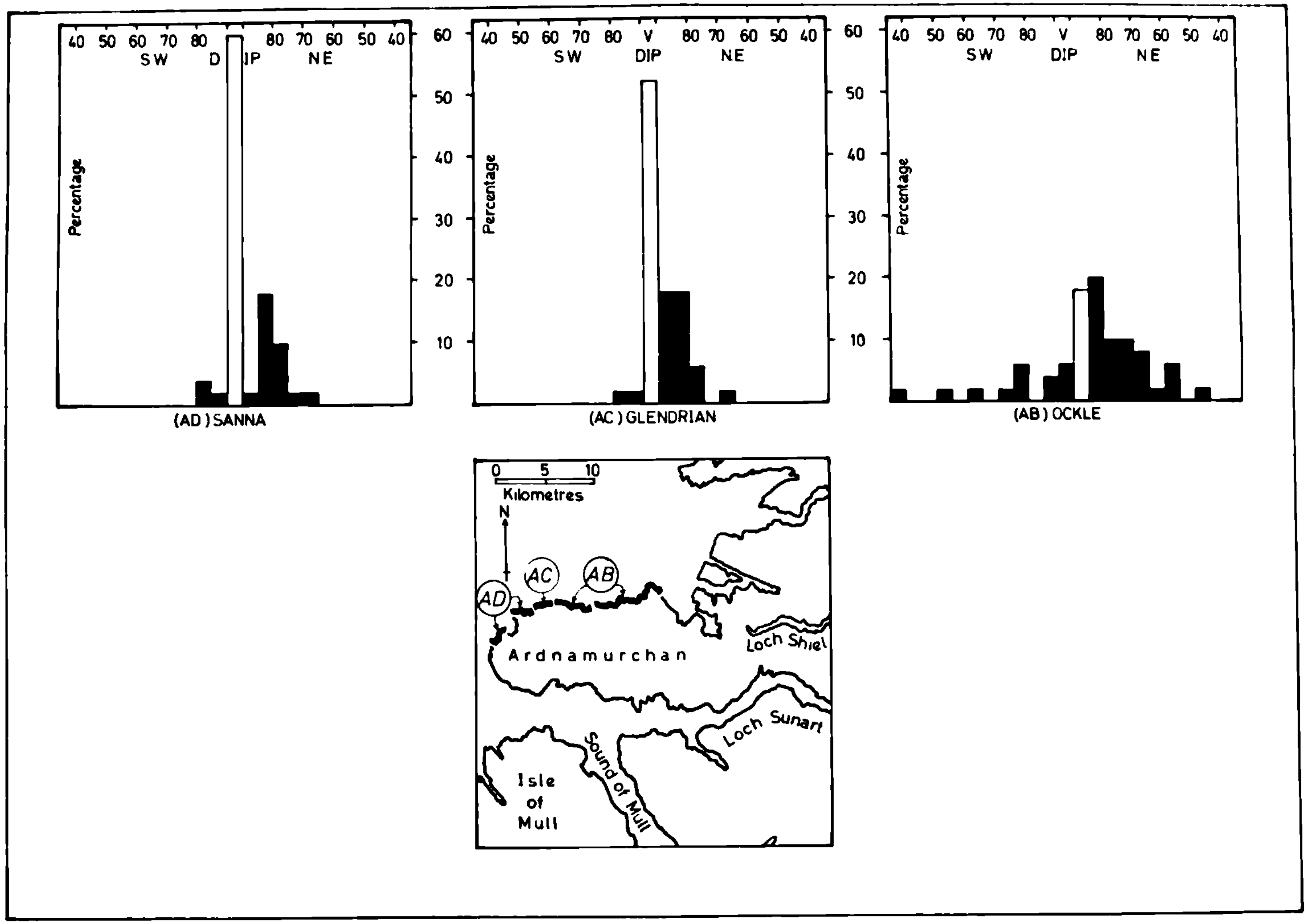


Fig.94. Dip-analysis

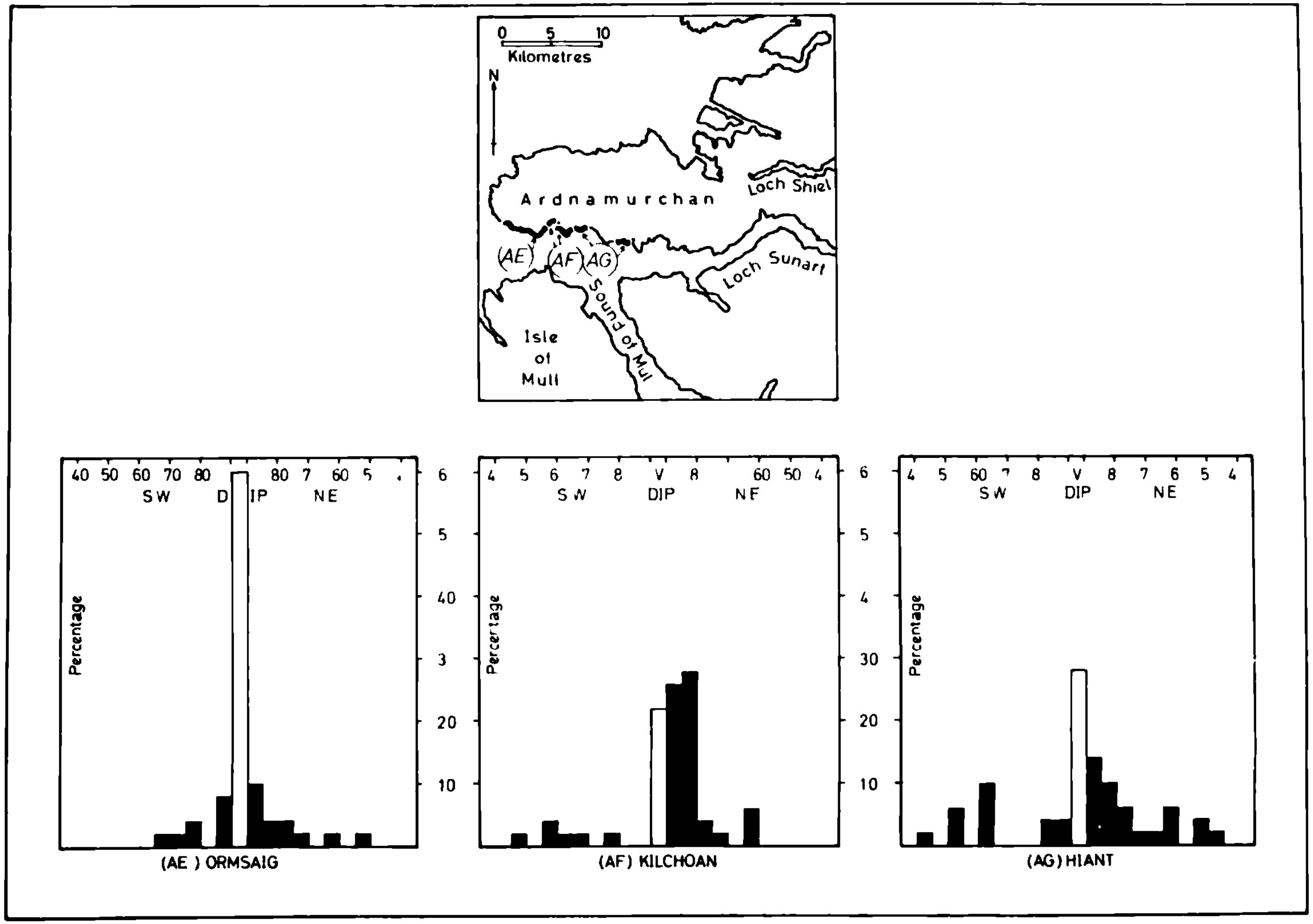


Fig.95. Dip-analysis

favouring of N.E. dips in most of the groups of figs. 94 and 95.

Some of the major characters of the geographical distribution of dykes of different dip are illustrated in the three contour-maps forming figs. 96 to 98, which are based on Appendix 16. The percentage-proportions of dykes which dip to N.E., to S.W., or which are vertical, are calculated for each of the 74 groups. The values for each of these three functions are allocated to the respective group centre-spots, and contours are roughly constructed. Projection of contours across the poorly-exposed area of central-northern Skye is less certain than in the cases of previously contoured functions, described in earlier chapters. Hence, this area appears blank on figs. 96 to 98. Contours on the three maps are at 10 per cent. intervals.

Fig.96 shows the geographical distribution of the vertical or sub-vertical dykes, i.e. of dip lying so near to vertical that classification into the categories of S.W. or N.E. dips is impracticable. Obviously, the range of interval to which vertical dykes are assigned is very much less than those intervals for S.W.- or N.E.-dipping dykes. Nevertheless, such vertical dykes reach high proportions in certain districts. Notable among these districts are Vaternish Peninsula, and the region to the north-west of the Cuillins. Both of these are located on prominent dilation-axes. Large

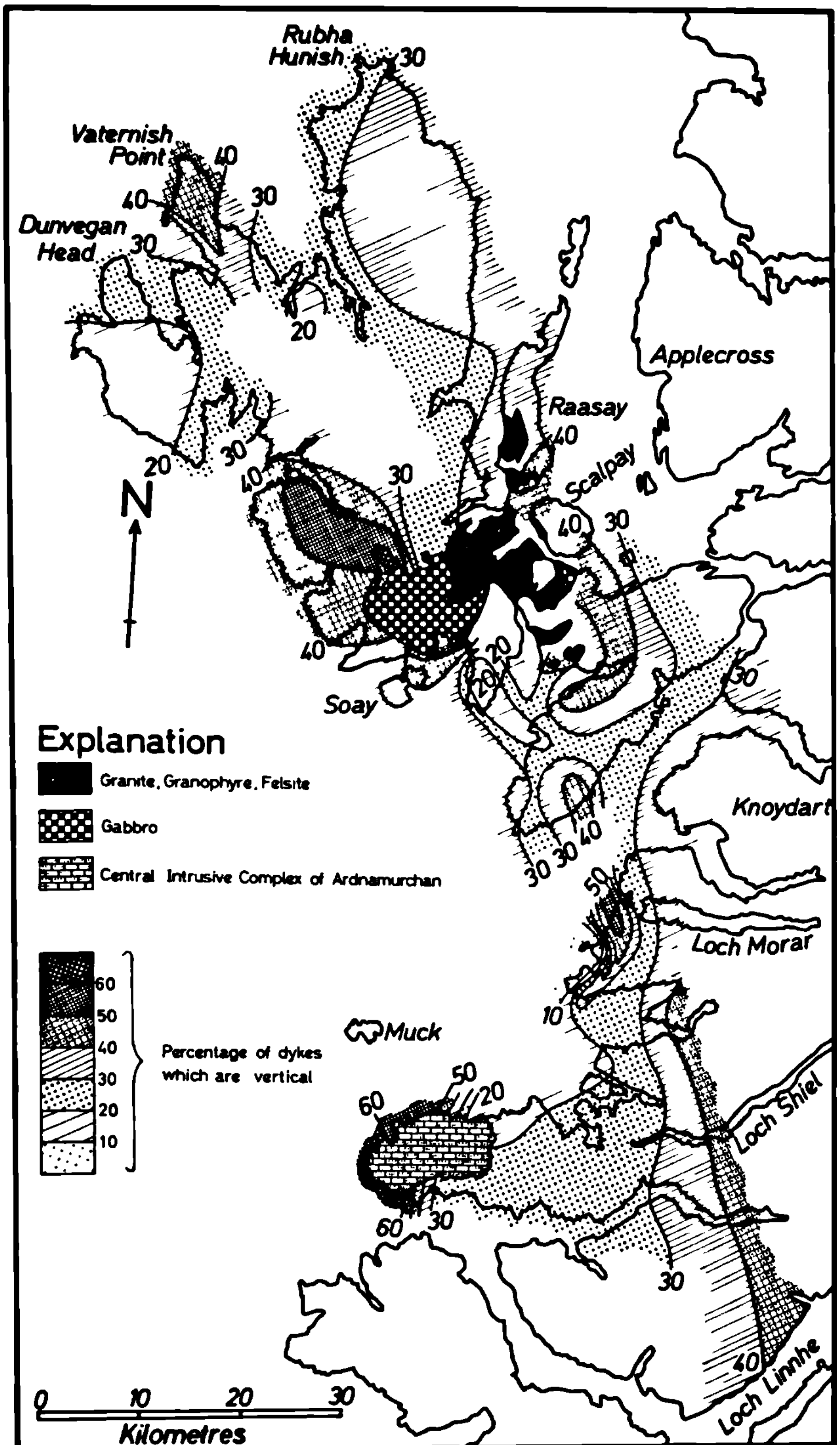


Fig.96. Contour-map to show the proportion of numbers of dykes which are vertical or near-vertical (based on values for groups of 100 & 50 dykes)

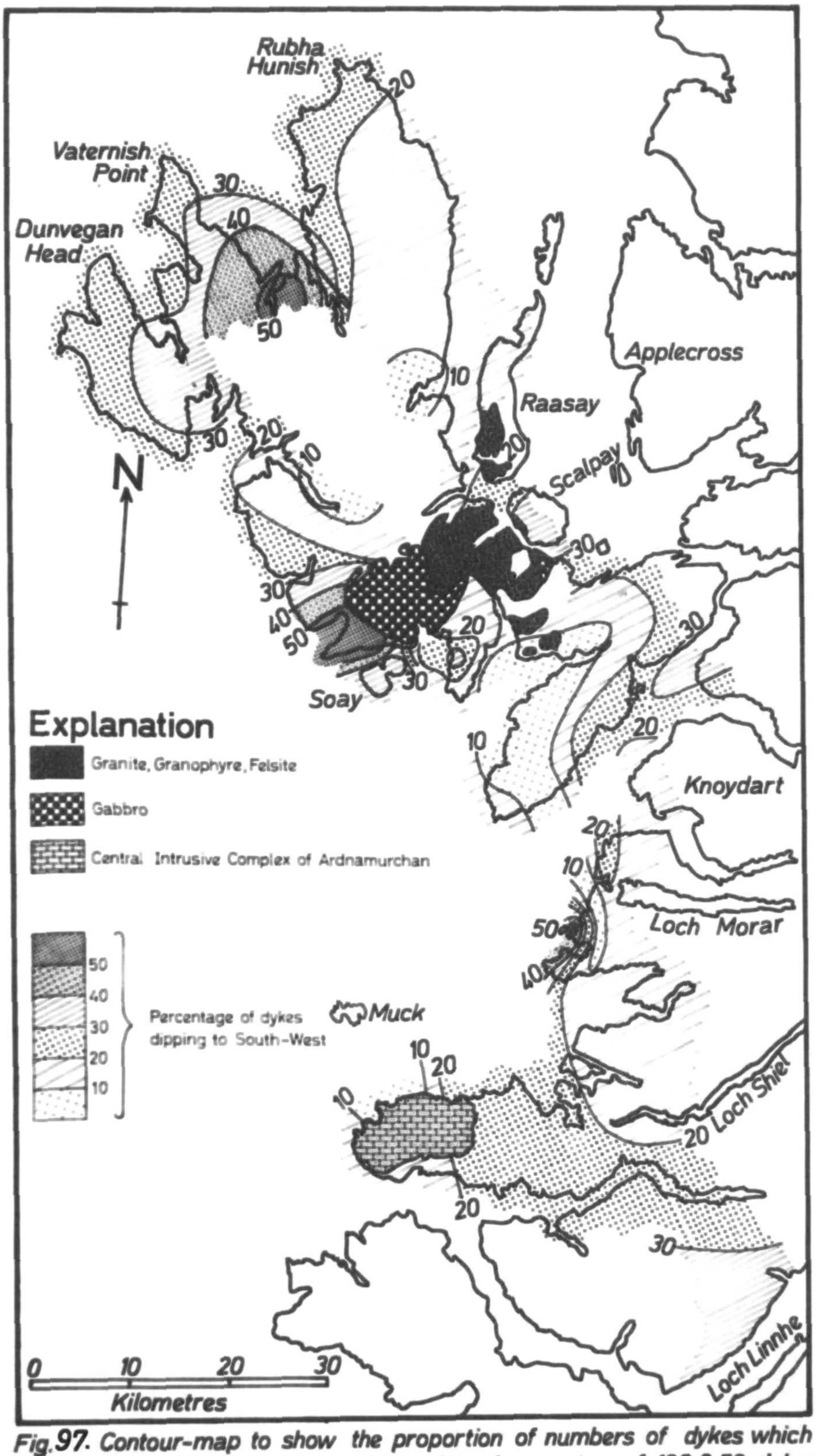


Fig. 97. Contour-map to show the proportion of numbers of dykes which dip to the South-West (based on values for groups of 100 & 50 dykes)

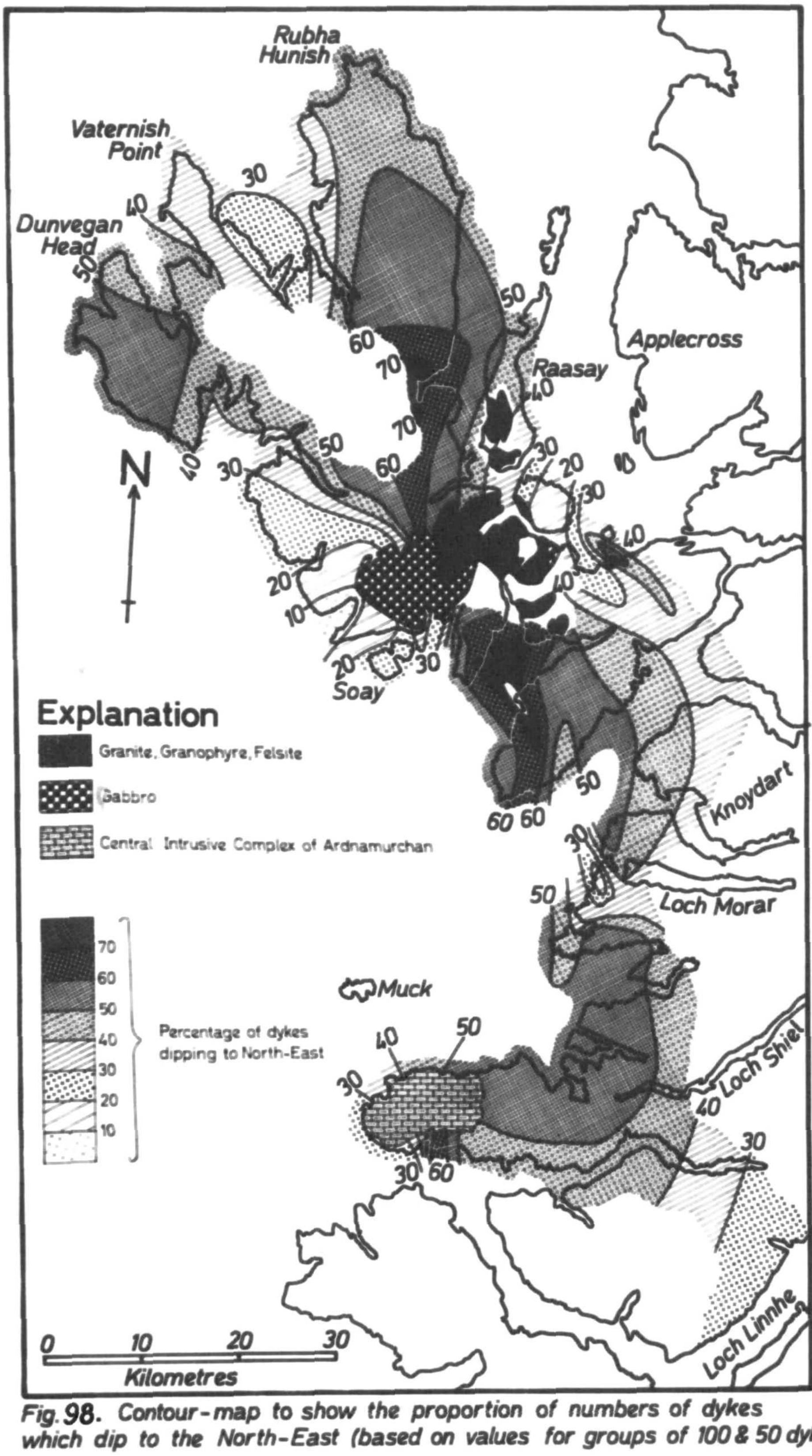


Fig. 98. Contour-map to show the proportion of numbers of dykes which dip to the North-East (based on values for groups of 100 & 50 dykes)

numbers of vertical dykes are located in the region of the dilation-axis extending from southern Sleat to Morar, at the western part of Ardnamurchan Peninsula, and at the location of the Scalpay Secondary-Swarm.

The dykes which dip towards S.W. (fig.97) are especially abundant in the district to the south-west of the Cuillins, around the head of Loch Snizort, and in Arisaig. They are markedly sparse in the north-east of Skye, in Strathaird and Sleat, in Morar and Moidart, and in western Ardnamurchan.

The dykes which dip towards N.E. (fig.98) are of the most widespread type. There is a paucity of them only in the district to the south-west of the Cuillins, and in the Scalpay region. Very large proportions of N.E. dips are found in the north-east of Skye, especially around Portree Bay, and also in Strathaird and Sleat, along the line of the main dilation-axis. Moidart has large numbers of dykes of N.E. dip. The south coast of Ardnamurchan, close by to the main axis of dilation at this locality, has a high proportion, too.

Like the attempts to produce a single illustration of the variation in the arithmetic-average trend and arithmetic-average thickness of the dykes, an attempt is made here to accomplish the same with the dip (fig.99). Once again, the frequency-distributions of the dip within the 74 groups indicate that such small numbers, as 100 or 50, are not suitable for demonstrating Gaussian-Distributions. It is not likely, in fact, in the case of the dip that a Normal-Distribution is the condition, whatever numbers are grouped and analysed. Consequently, an arithmetic-average value of the dip is by no means a truly statistically valid function.

The calculation of an average value of the dip of the dykes is problematic. Suppose that a number of dykes originate from one position at depth, x, below the surface. . Because of their different dips, the dykes meet the surface at differing distances from the spot on the surface vertically above their point of origin, say y_1, y_2, y_3, etc. By analogy with simple mechanics, the "moment" of each dyke about that spot on the surface is a multiple of its distance from the spot. The cotangent of the angles of dip are y_1/x, y_2/x, y_3/x, etc. Hence, the "moment" is proportional to the cotangent of the angle of dip. The sum of the "moments", on either side of the spot on the surface, gives the resultant "moment" of the whole, either to one or the other side of that spot. Hence, the value of the sum of the cotangents (say, S.W. dips being negative, N.E. dips being positive, and vertical dips being zero), divided by the total number of dykes in the group (including vertical dykes), is the cotangent of the average dip of that group of dykes.

In many ways fig.99 (data in Appendix 17) summarizes the detailed analyses described above. The average dip towards N.E. reaches minimal values around Portree (less than 86deg.), and through Sleat to Loch Sunart, excluding a district in Arisaig. These "highs" reflect the proportionately larger numbers of dykes dipping towards N.E. in these areas. The contours in Sleat, through to Morar, and in Moidart to Loch Sunart, each are disposed about a definite axis. In each case, this axis approximately coincides with a dilation-axis.

Districts in which the average dip is towards S.W. are: (i.) south and west of the Cuillins, (ii.) along a region approximately parallel to the dilation-axis of the Scalpay Secondary-Swarm, (iii.) north-central and north-eastern Skye, and (iv.) Arisaig. The division between districts in which average dips are towards S.W., and those where they are towards N.E., is indicated by a thick solid line on fig.99. Along this line the average dip is vertical.

To a certain degree the disposition of the dips of the dykes around the Central Intrusive Complex of Skye is radial. A S.S.W.-trending axis of S.W.-dipping dykes is located at Glenbrittle; a less pronounced axis of N.E.-dipping dykes runs northwards towards Portree; to the east of the Central Complex, S.W.-dipping dykes are prominent again; to the south and south-east, average dips are towards N.E. In the

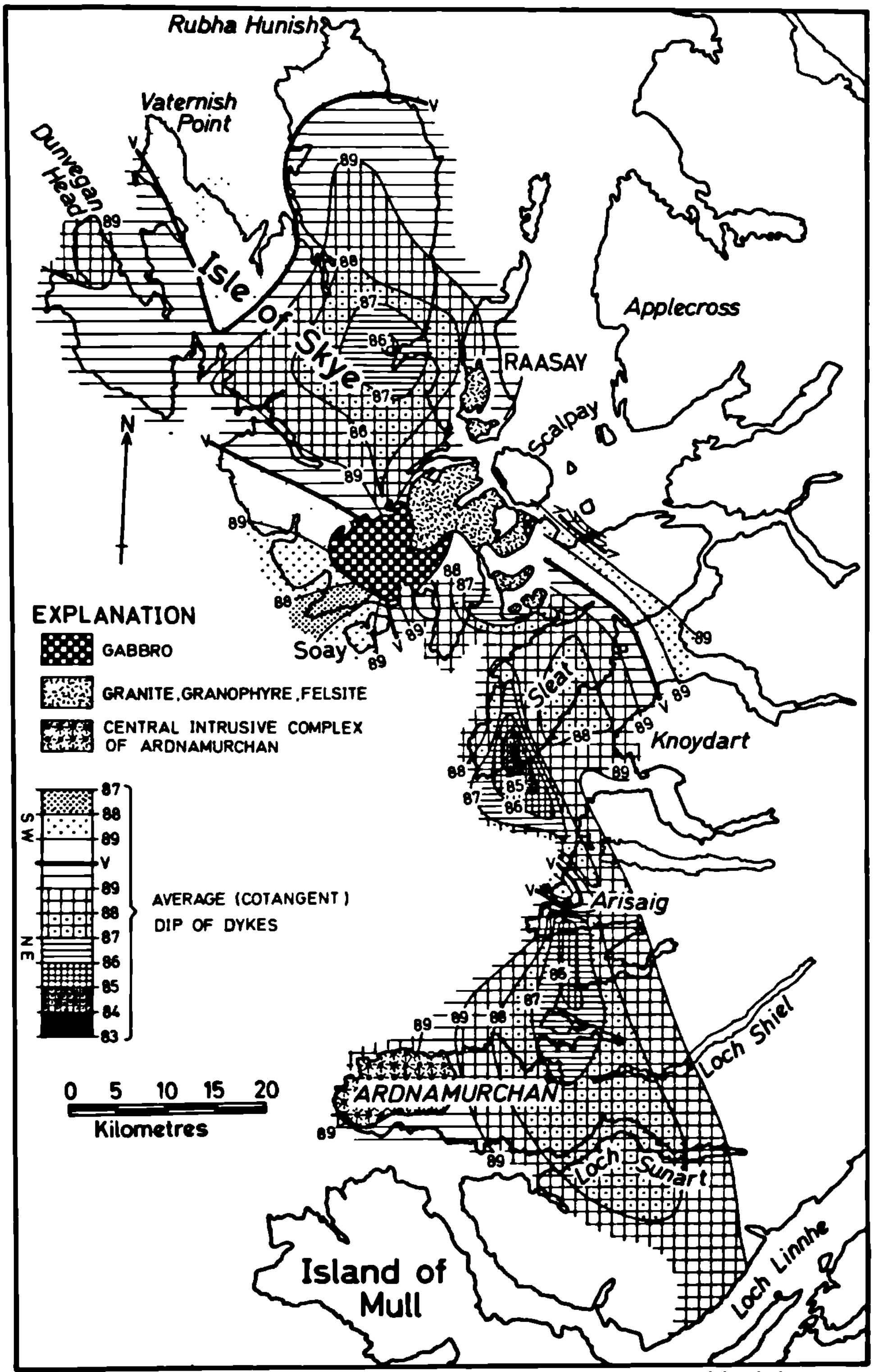


Fig. 99. Average dip of dykes (based on sum of cotangents of hade)

latter two areas, the "radial" disposition of the dips is complicated by the Scalpay Secondary-Swarm.

The dips of the dykes on Ardnamurchan, on the other hand, do not exhibit such a radial distribution, and show no great deviation from an average of vertical.

In Chapter Six (V), the analyses of the trends of the dykes included the geographical distributions of the standard-deviation and of the "normal"/"abnormal" frequency-distributions. Such analyses of the dip are not attempted, largely because the interval in which vertical dykes are allocated is not equal to the 5-deg. intervals used for dipping dykes. Moreover, as mentioned above, Normality of dip is not a character to be expected within individual groups. The asymmetry of the frequency-distribution is due to the combination of two factors: (i.) the generally high proportions of vertically-inclined dykes, and (ii.) the usual dominance among the other dykes of dips either towards N.E. or S.W.

It is especially important that the results of the analyses of the dips of the dykes be related to the other properties of the swarms, notably to the positions of the dilation-axes. In this connexion, totally-exposed traverses lying at right-angles to the main axes of dilation would be valuable assets. Unfortunately, such traverses are rare. As substitutes, poor though they are, with their many attendant disadvantages, areas are selected which contain numbers of short traverses, the aggregate extents of which are as nearly as possible equivalent to totally-exposed E.N.E. to W.S.W. traverses across the whole breadth of the swarms. Such areas are 1 and 2 (fig.100) and the area depicted on fig.104. There yet remain strips within these (not ornamented) which include no exposed traverses.

The E.N.E. to W.S.W. direction is chosen for the section since this lies at right-angles to the median trend of the dykes. In some respects, the sections may have been more aptly orientated at right-angles to the trend of the main dilation-axis in each area. A perpendicular is dropped from each recorded dyke to a point on the line of section, and the amount of dip of the dyke is plotted above or below that point (for N.E. or S.W. dips, respectively), ar at that point for vertically-inclined dykes. Figs. 101, 102, and 105 are the results. Along Section 3 (figs.100 & 103) the data is derived from dykes outcropping along a single (though broken) traverse. This particular traverse is far from an ideal E.N.E. to W.S.W. trend, and equally far from a direction at right-angles to the line of the main dilation-axis passing through southern Sleat.

One of the problems encountered in the construction of these sections is most prominently displayed in Section 1 (fig.101). Because this section is at right-angles to

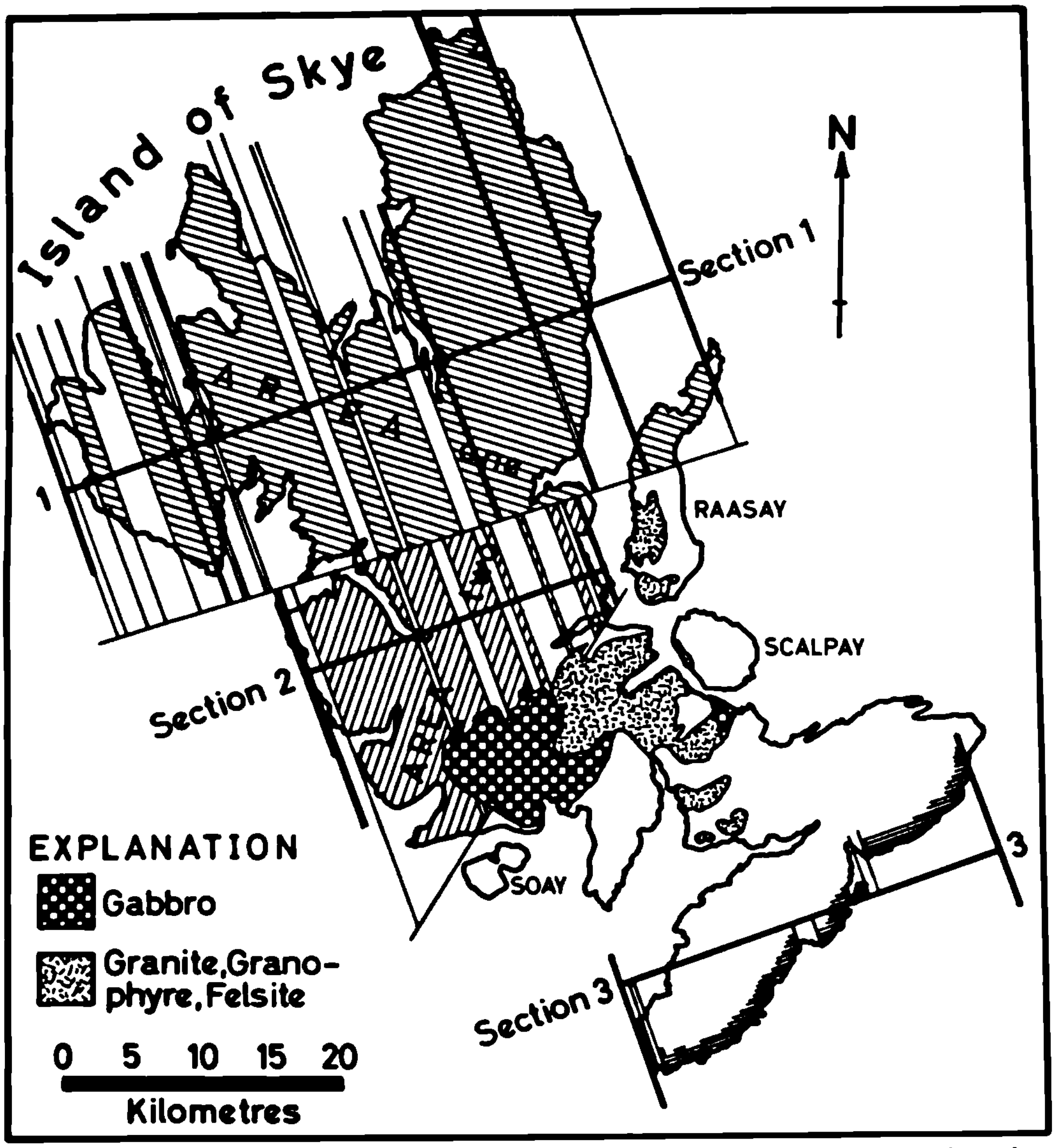


Fig.100. Sketch-map of Skye and the adjacent islands, showing locations of Sections 1,2 & 3, for analyses of the dips of dykes.

(Diagonal lines marked in "AREA one" and "AREA two" indicate N.N.W.- S.S.E. oriented strips, along traverses within which there are recordings of dykes. The band of more closely spaced lines on the southern coast of Skye indicates the extent of the observations along a traverse along the shore, and does indicate any land-ward extent of the exposures)

N.N.W., and not perpendicular to the line of the dilation-axis at Vaternish, plots near the axial region (fig.101) include the dips of dykes in the district around Loch Bracadale (fig.4, for location) , i.e. a district in which lies the lesser dilation-axis 1A (fig.48).

By no means is there a simple distribution-pattern of dips to the E.N.E. and W.S.W. of the position of the dilation-axis in either of figs. 101 and 102. Higher proportions of vertical dykes in the neighbourhood of the axial positions (figs. 101 and 102) are evident. The very general change from a preponderance of S.W.-dipping dykes to one of N.E.-dipping dykes, in passing from districts lying to the south-west of the Cuillins to the districts of north-eastern Skye and Raasay (figs. 101 & 102 in combination) is also obvious. In this latter respect, the S.W. dips of dykes in the Loch Snizort district (fig.4, for location), to the E.N.E. of the line of the axis at Vaternish (fig.101), are somewhat anomalous. (Fig.45 includes a separate analysis of the dips of the dykes near dilation-axis 1A (fig.48). N.E. and S.W. dips are to some degree symmetrically disposed about this axis.)

The general lack of any outstanding symmetrical arrangement in either of figs. 101 and 102 indicates that structural control on the dips is far from simple, and may have changed with time. The overall abundance of vertical dykes

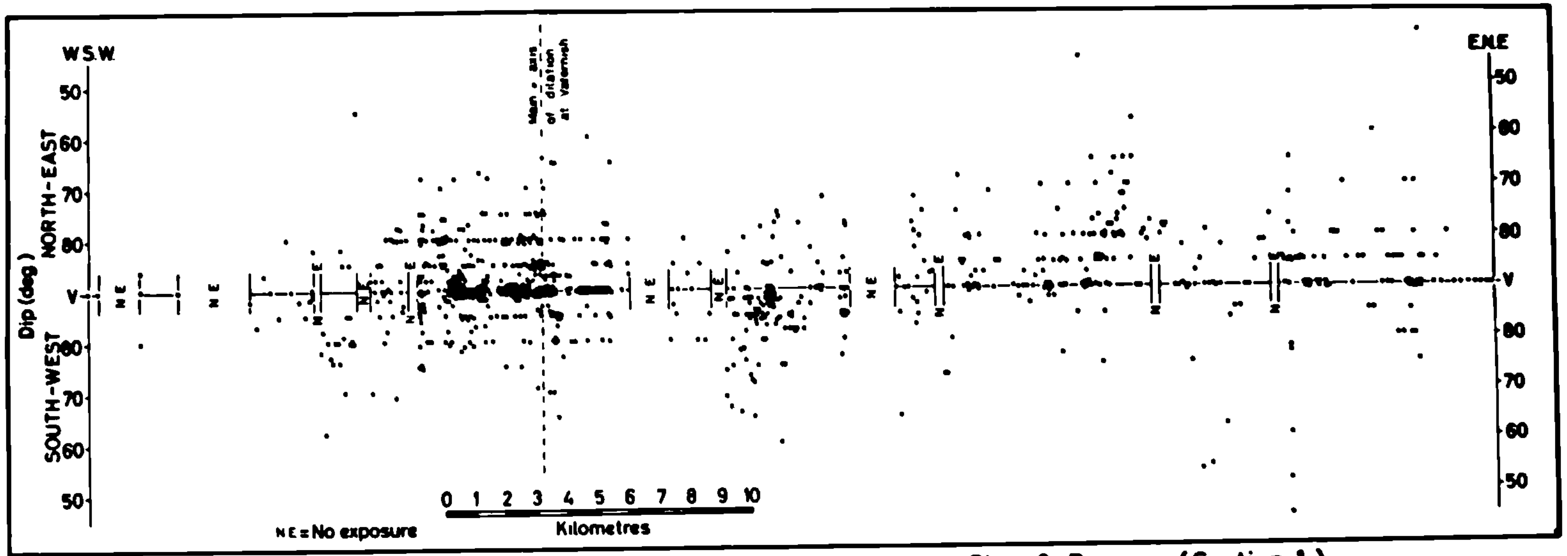


Fig. 101. Graphical analysis of the dips of the dykes in northern Skye & Raasay (Section 1).

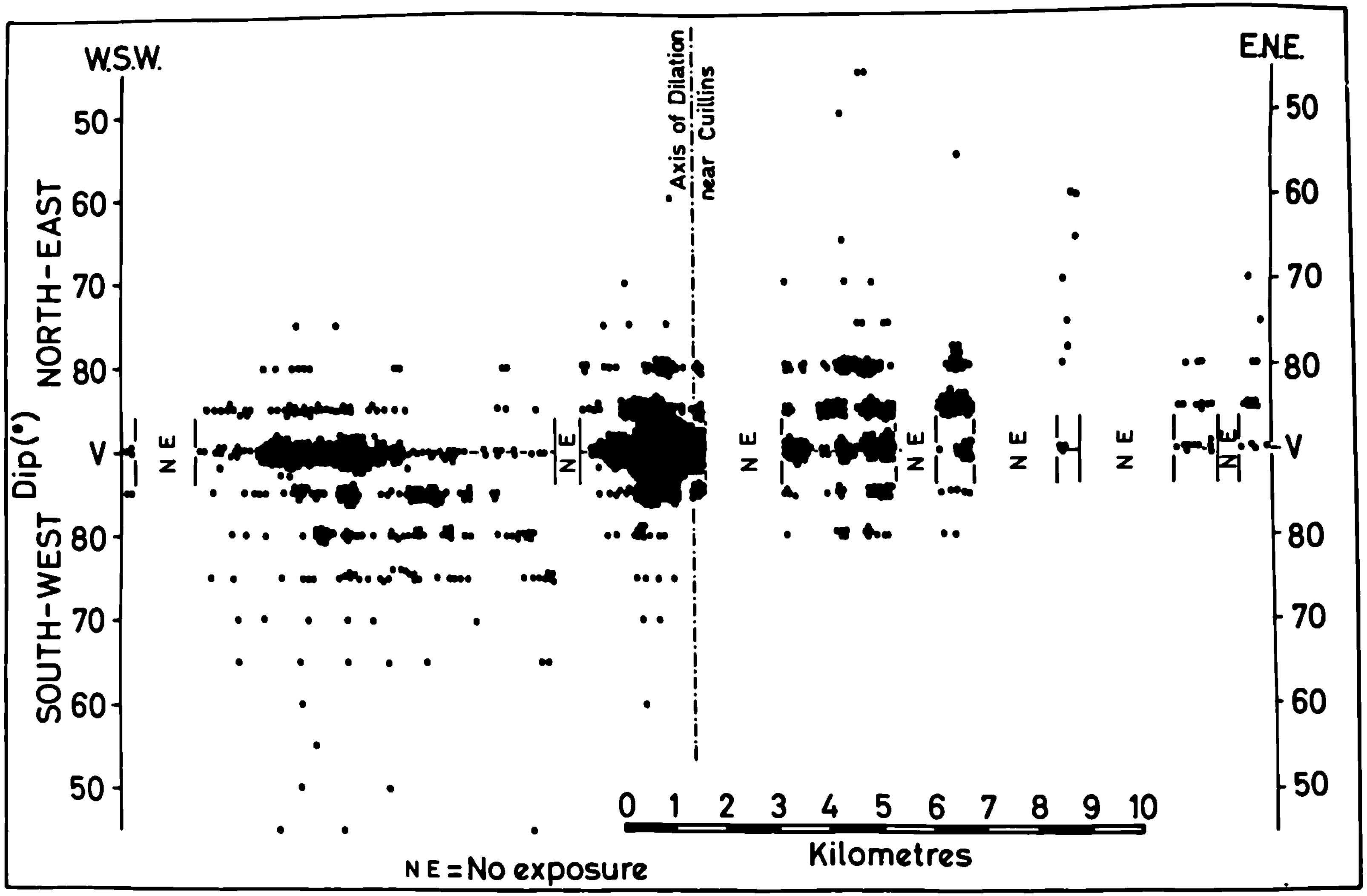


Fig. 102. Graphical analysis of the dips of the dykes in north-central Skye (Section 2).

in Area 2 (fig.100, and Section 2, fig.102) may signify a polygenetic origin of the dykes, with some belonging to the regional-swarm and others "flushed out" from the Central Intrusive Complex.

Fig.103 shows a similar lack of marked symmetry of dips about the position of the dilation-axis. The dykes dip towards N.E. or are vertical, although S.W. dips are far from absent.

Section 4 (fig.105) extends across the limits of the Ardnamurchan and Skye Swarms (fig.104). In the Ardnamurchan -Swarm there is a preponderance of vertical dykes in the neighbourhood of the dilation-axis, and inclined dykes are mostly of N.E. dip, with proportionately fewer S.W. dips. In the Skye-Swarm, in Moidart and Sunart, dykes of N.E. dip predominate in number over, and have a larger spread than, S.W.-dipping dykes, whilst vertical dykes are proportionately few.

10:III. Significance of the Dip of the Dykes.

The analysis of the dip of the dykes is perhaps the most difficult aspect of the research. The possible controls which influence the dip of a dyke are many. Added to the complication of the variety of controls is the fact that most of them may have altered in character with time. It is true that the controlling structures within the Moinian rocks and the possible controls exerted by the Torrid-

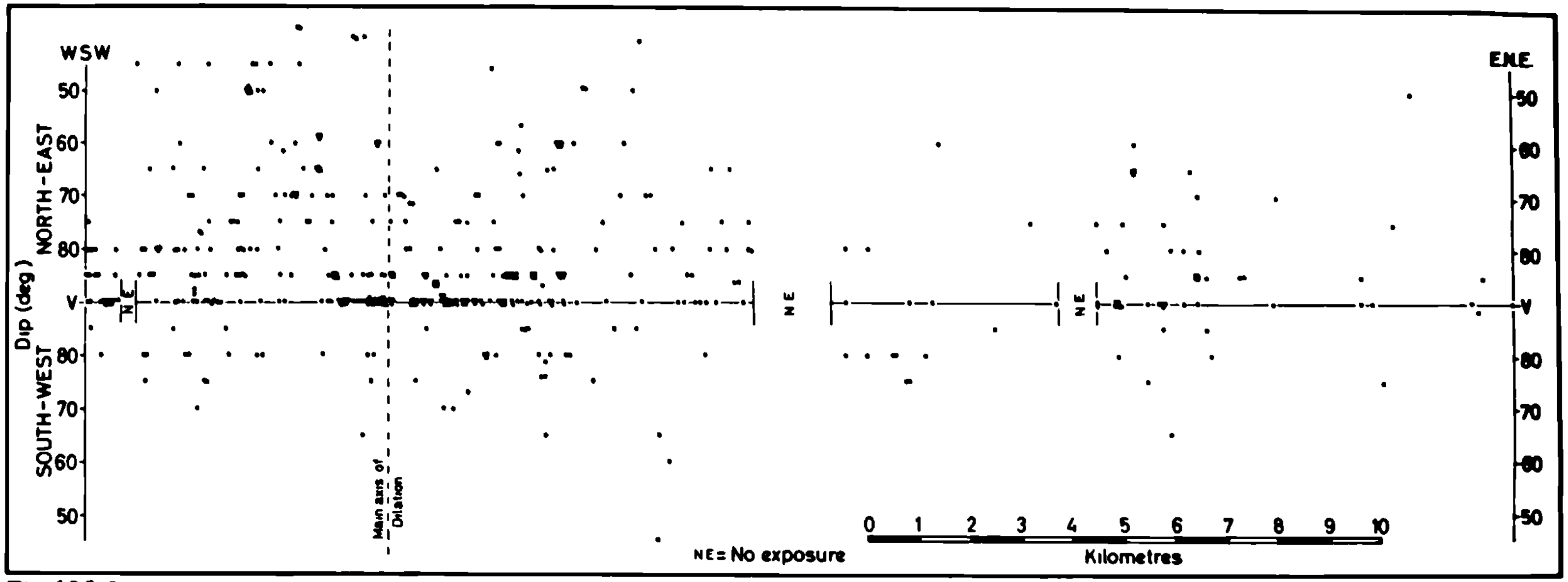


Fig.103. Graphical analysis of the dips of dykes along the southern coast of Skye (Section 3).

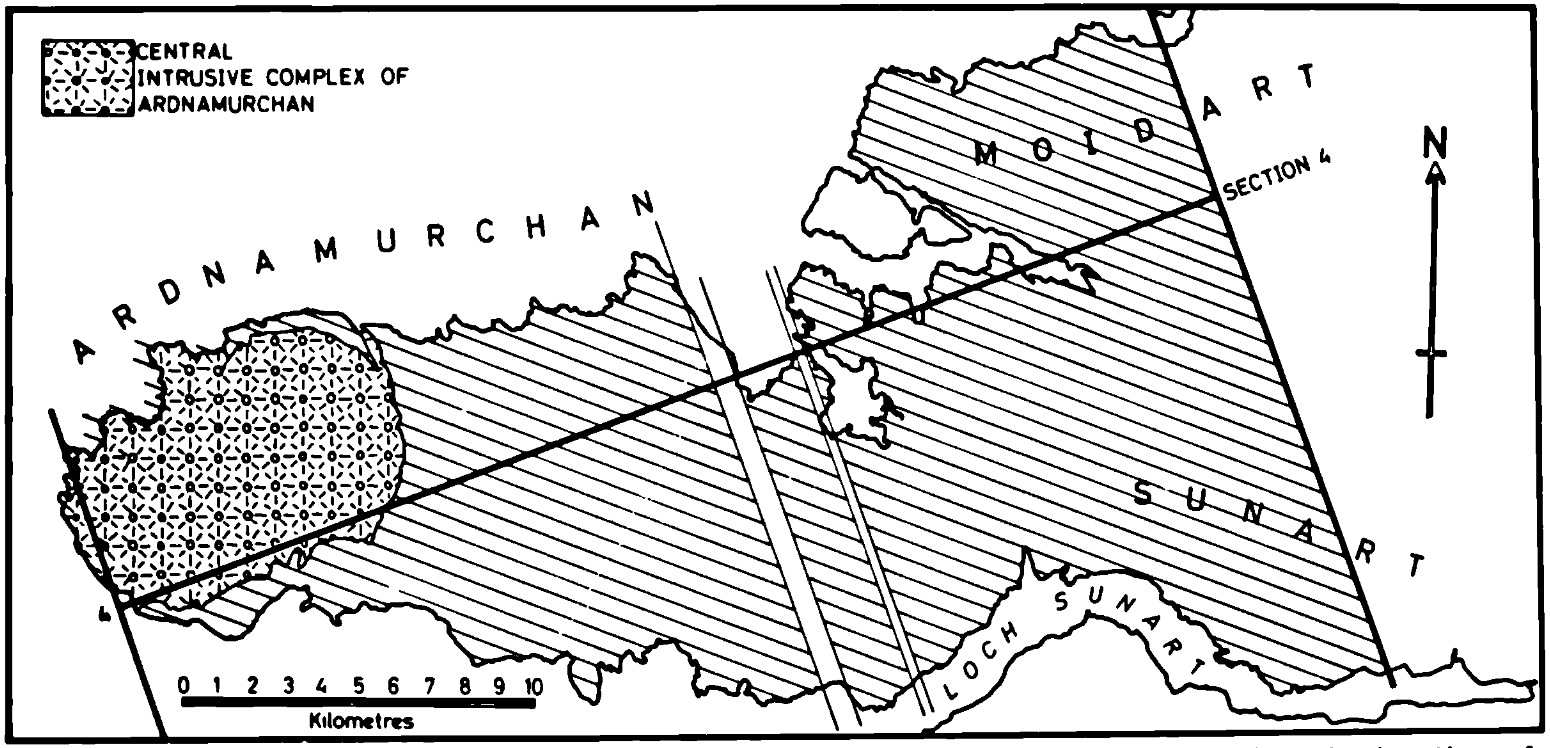


Fig.104. Sketch map of the districts of Ardnamurchan, Moidart and Sunart, showing the location of Section 4 for an analysis of the dip of the dykes. (Diagonal lines indicate NNW-SSE oriented areas-strips-along traverses within which there are recordings of dykes)

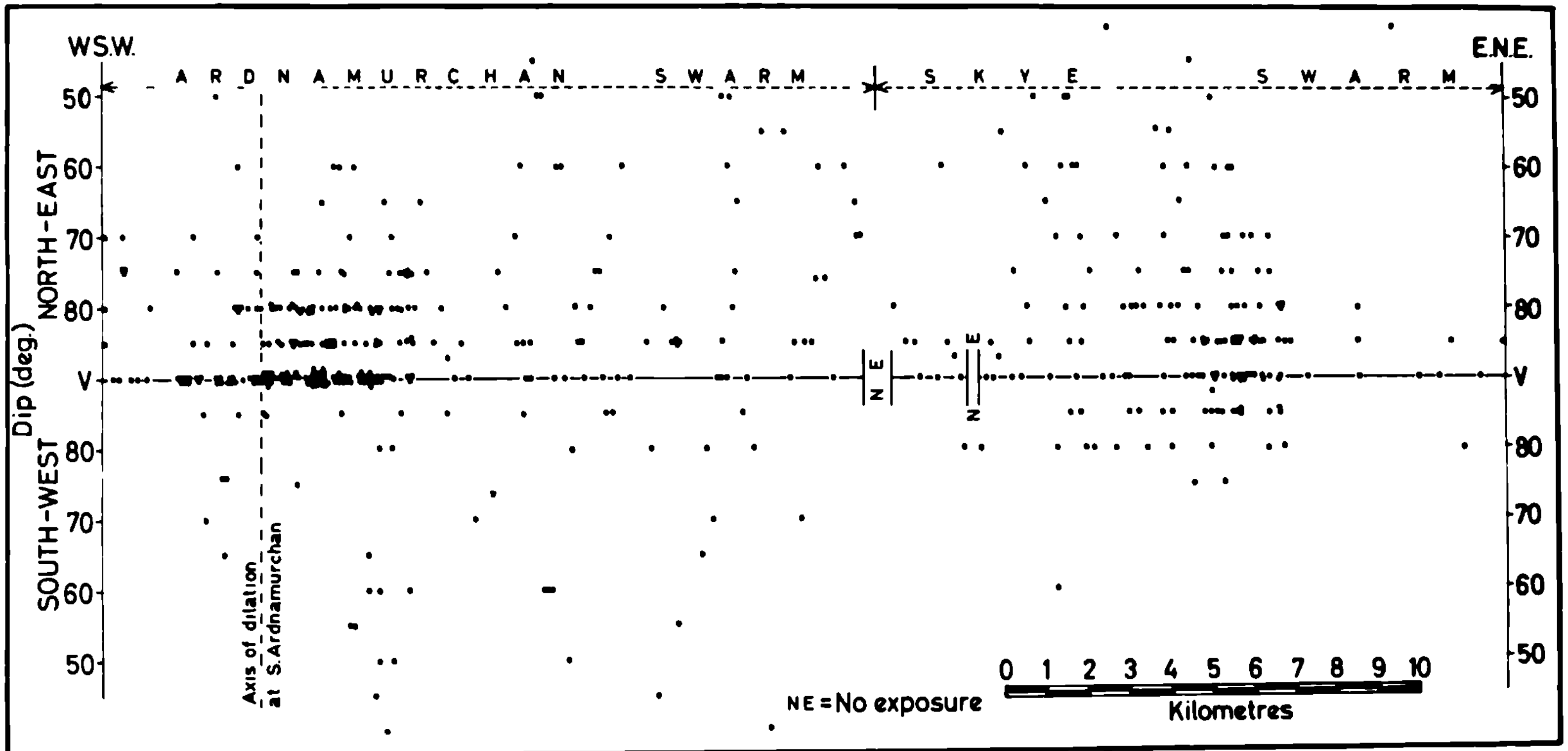


Fig. 105. Graphical analysis of the dips of the dykes in Ardnamurchan, Moidart and Sunart (Section 4)

onian rocks are likely to have remained constant in their orientation throughout the period of dyke-injection, but the effect of structural changes in the form of the lava-pile and the effect of the intrusions of the Central Complexes are not of such a constant nature. The problems of interpretation would be much simplified if the ages of the individual dykes were known.

The relationship between the form of the lava-pile and the dips of the dykes intruded into it is not so simple that the dips of the dykes are at right-angles to the dips of the lavas. Even if they were, the question would still arise as to whether the dykes were intruded vertically and were later tilted along with the lavas, or whether the dykes followed planes of weakness formed during "basin-ing" of the lavas. This latter problem would be soluble if by some means it could be determined whether the present dip of the dykes is a primary or secondary feature. The positions of layers of amygdales within a dyke — of all too rare an occurrence — is of little help in this respect. Both the case where amygdaloidal bands are centrally or symmetrically situated and the case where they are found only on the hanging-wall of an inclined dyke are observed, for dykes outcropping in the same area and dipping in opposite directions. The former case strongly indicates an original vertical intrusion; the latter indicates an originally inclined intrusion.

Anderson and Dunham (1966,pp.90-2) postulated that the collapse of the roof of a main magma chamber, which lay under the interleaved and overlapping series of lava-flows, led to a basin-ing of the lava-pile. The supposed earlier collapses of the local reservoirs, which Anderson and Dunham described as "shallow offshoots from the main magma mass" (1966,p.90), must also have led to some folding of the already extruded lavas. The last phases of tectonic activity, namely the block-faulting and the postulated tilting of the area towards the west, further complicated the structure of the lava-pile.

The general preponderance of N.E.-dipping dykes throughout the whole Area of Study could conveniently be ascribed to this late-stage westward tilting, although the evidence for such tilting is based on a circular argument in which the dips of the dykes are used as evidence of its reality. The vertical dykes and dykes of S.W. dip are not so easily dismissed. The dominance among the dykes of S.W. dips in regions to the south-west of the Cuillins, and of N.E. dips in north-east Skye, can be correlated with the locations of these areas on the limbs of the major basin-form of the lava-pile. The equal proportions of vertical, and S.W.- and N.E.-dipping dykes near Vaternish (compare figs. 96,97,&98) are compatible with the siting of this area both at the axis of collapse of the lava-pile and at the main axis of dilation.

The overall variability of the dips of the dykes, within any one area in the lava-pile, may in part be due to the collapses of local reservoirs and the effects of these on the overlying lavas. Such lavas may locally have been folded into shallow anticlines, synclines, monoclines, etc., with a resultant development of possible planes of weakness. The anomalous dominance of N.E.-dipping dykes at Dunvegan Head may be an example of such a phenomenon.

Not only the collapse of the lava-pile, but also the intrusion of the Central Complex must be considered, especially in dealing with an analysis of the significance of the dips of the dykes in the near vicinity of this body. Such a large intrusive mass would obviously have considerable disturbing effects on the original dip of nearby already intruded dykes, and possibly the sub-radiate disposition of the dips of the dykes around the Cuillins (described above) is related directly to the emplacement of the Central Basic Complex.

The variability of the dips of the dykes in the areas outside the lava-pile introduces yet another complication in the interpretation of the significance of the dips. Where the dips of the dykes are not obviously related to the local structures within the pre-Tertiary country-rock, then reasons for the distributions of the dips must be sought at a deeper level or must be of a regional character. If the crustal-rocks were tilted westwards after the emplacement of the dyke-swarms, then how can the not infrequent occurrence of dykes inclined towards S.W. be explained? Again, the factor of time may be of great significance.

Some further comments on the origin of the dips of the dykes are made later (Ch.15:III,b; 16:VI,4&8).

10:IV. <u>Dip of Dykes of the Subswarms</u>.

In the Scalpay-Subswarm about 60 per cent. of the dykes dip towards S.E., 30 per cent. are vertical, and about 10 per cent. dip towards N.W. The inclination of the dykes is usually steep, and few dip at less than 80-deg.

In the Glenbrittle-Subswarm about 50 per cent. of the dykes dip towards N.W. or N., about 25 per cent. are vertical, and 25 per cent. dip towards S.E. or S. Again the dykes are mostly steeply inclined, with only a few dykes dipping at less than 75-deg.

In the Broadford Bay-Applecross Subswarm, about 55 per cent. of the dykes dip towards E., S.E., or S., 35 per cent. are vertical, and 10 per cent. dip towards W., N.W., or N. The dips are generally steep, but there are some slightly shallower dips towards N.W. in dykes outcropping on Pabay, and more especially at Rubha Suisnish.

In all the subswarms, the geographical distribution of the dips is random in as much as, for instance, dips towards N.W. and S.E. are not symmetrically arranged about the axes of dilation, nor dependent upon the distance of the dykes from the Central Intrusive Complex.

In the vicinity of Loch Sligachan and Portree, the dips of the dykes of the regional linear-swarm are chiefly towards N.E. or E. In the Broadford Bay-Applecross Subswarm the dips of the dykes are mainly towards E., S.E., or S. In the Scalpay-Subswarm the preponderant dip is towards S.E. The general "clockwise nature" of the dip is sustained throughout these three swarms in this district.

In the Glenbrittle-Subswarm the dominant dip is towards N.W. or N. On the other hand, the dip of the dykes of the N.N.W. linear-swarm is mostly towards S.W. In this case, the sense of the dip in the two swarms is opposite. The sense of the dip in the two N.E.-Subswarms is also opposite. Despite the fact that the dilation-axes of the two N.E.-Subswarms are in alignment, this additional information is permissible though flimsy evidence in favour of the opinion that they are of different ages of formation. In Chapter Seven (VIII), the opposite of this theory was stated.

Chapter Eleven

THE TERTIARY DYKES
OF THE SMALL ISLES OF INVERNESS-SHIRE

11:I. Introduction.

In the summer of 1969, a study of the Tertiary dykes of the Small Isles of Inverness-shire was undertaken. The initial purpose of the study was for the author to present an account, entirely separate from this thesis, of the results of the analyses of these dykes. Since these results significantly add to and reinforce the deductions on the form and structure of the swarms of Skye and Ardnamurchan, this chapter is now appended to the thesis. In part, the aspect of the chapter remains that of a discussion segregated from the preceding chapters. This lack of integration is superficial only, and is a consequence merely of the posteriority of the work to the bulk of the researches.

Richey (1939,p.423) indicated that the dykes of Muck are in all probability members of the Ardnamurchan Regional Linear-Swarm. A study of the dykes outcropping in the Small Isles of Inverness-shire, viz. Rhum, Eigg, Muck, Canna, and Sanday, is necessary for an assessment of the degree of this probability. The general geological scope and aims of the researches on these dykes are much the same as those outlined for the swarms of Skye and Ardnamurchan. The work on the Small Isles not only broadens the knowledge of the Tertiary Hebridean Swarms, but also provides more information on separation or connexion, form and structure, and mechanisms of genesis, of dyke-swarms.

11:II. Review of Previous Work.

Little can be added here that has not already been said (Ch.2). As well as making comments on other Hebridean swarms. MacCulloch (1819), Judd (1874), Geikie (1889, 1897B), and Harker (1905) made similar remarks on the dykes of the Small Isles.

Geikie (1871,pp.298-303) described the major features of geographic distribution and petrology of the dykes and veins — including the pitchstone varieties— of Eigg.

Harker (1908,pp.143-61, 168-9, 176-81) described the distribution, trend, and the petrography of the dykes of all five islands. He noted that the dykes of Rhum have a radial distribution, due (he thought) to the influence of "local" causes, and that they focus on the Glen Harris district (1908, pp.144-5, including plate III), their frequency increasing towards the Central Complex. Dykes emplaced in the acid bodies of Rhum, however, were generally found to be non-radial. Harker (1908, pp.145-6) attributed the low intensities of dykes in the acid plutonic bodies of Rhum and in the agglomerates and conglomerates of Canna to the degree of impenetrability of these rocks. In Eigg and Muck the dykes are of normal N.W. trends. Harker attributed the high intensities (up to one-fifteenth of a traverse) in Muck to the proximity of the base of the lava-pile (1908, p.148). He also described (1908,pp.61-7) some vertical crush bands in northern Rhum, which occasionally contain dyke-like bodies, and concluded that these may have been fissure-feeders to the lavas.

Harker's belief in the radial character of the basic dykes of Rhum was reiterated by Richey (1961,pp.96-7: first edition, 1935). Fig.106 (taken from Richey,1961,p.97) illustrates these radial basic dykes and associated sparsely developed cone-sheets.

Richey (1939,p.423) considered that the dykes of Muck might belong to the Ardnamurchan-Swarm. Despite this precedent, the present author finds that the intensity-distribution of the dykes of Muck indicates that it is more sensible for descriptive purposes to include those dykes within the general category of the dykes of the Small Isles, even though a small proportion of their numbers might be genetically related to the Ardnamurchan-Swarm.

11:III. Geology of the Area.

The chief lithological groups outcropping in the Small Isles are illustrated in fig.107. The following account of the geology of the Small Isles is restricted largely to the lavas, Central Complex of Rhum, and the sills, as it was also for Skye and Ardnamurchan and for the same reasons (Ch.3:I). For descriptions of the pre- and post-Tertiary geology of the Small Isles, reference must again be made outside this present work (e.g. Harker,1908; Bailey,1944;

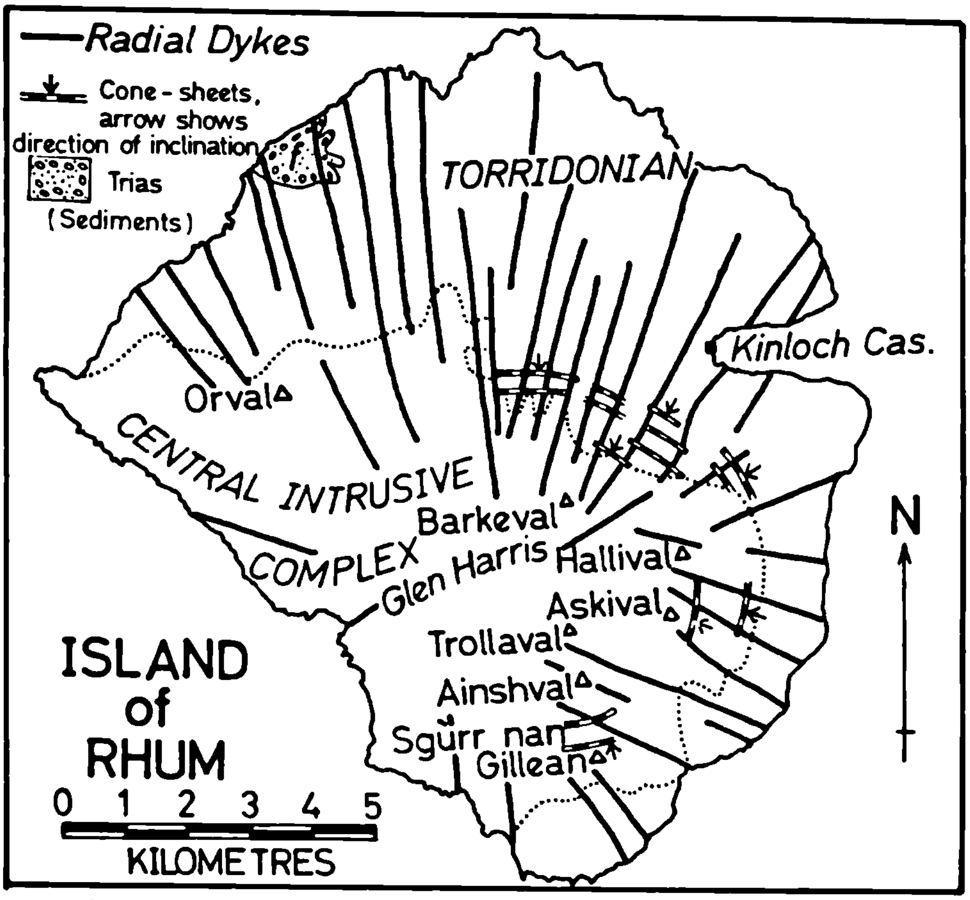


Fig.106.Trends of Radial-Dykes and Cone-sheets of Rhum. Based on fig.50, British Regional Geology, Scotland: The Tertiary Volcanic Districts, H.M.S.O., 1961.

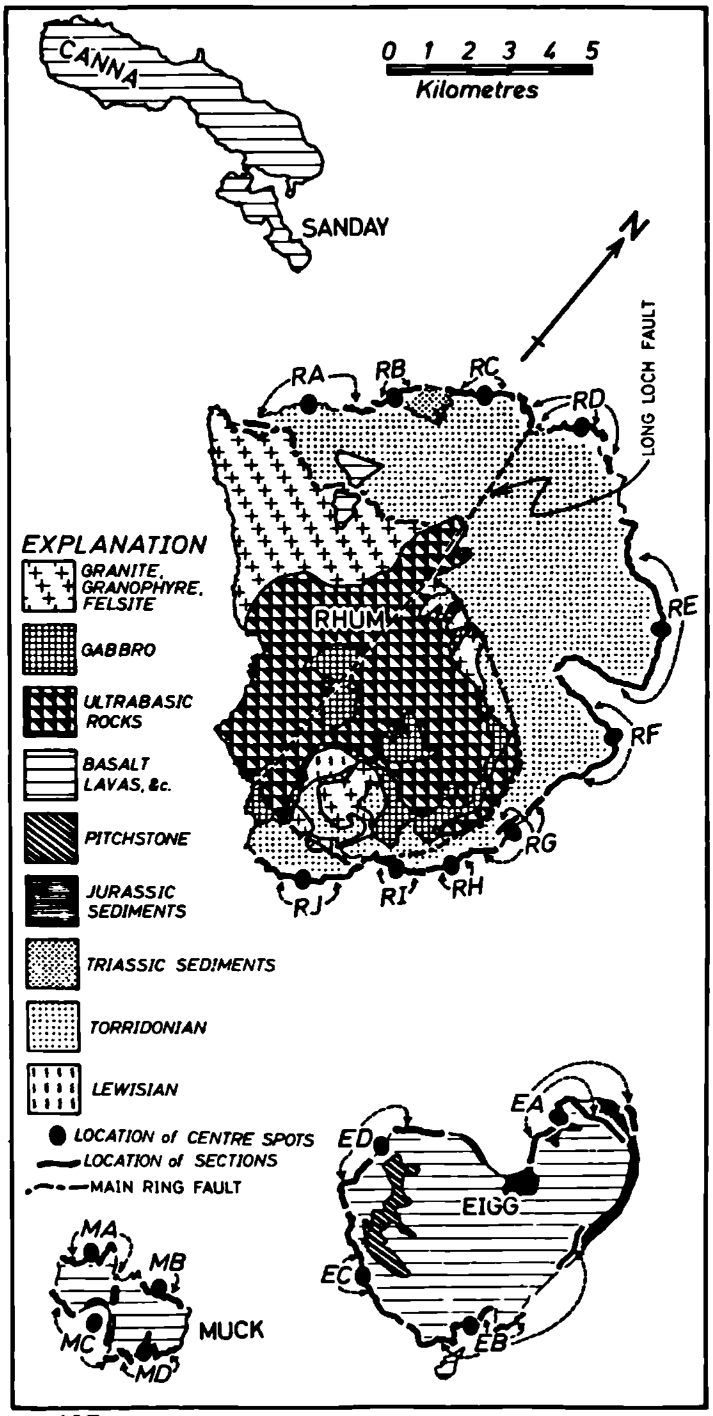


Fig.107. Sketch-map showing the geology of the Small Isles (after map prepared by Dunham and Emeleus (1967), and from 1-in Sheet 60, Geol. Surv., Scotland).

Location of sections and centre-spots for groups of 50 dykes — RA-RJ (Rhum), EA-ED (Eigg), MA-MD (Muck).

Tilley,1944; Geikie,1871).

Tertiary Lavas. The Tertiary lavas of the Small Isles, of which only four small outliers remain in Rhum (Black,1952A, p.49), are of much the same type as those in Skye (Harker, 1908,p.60), and total about 500m. thickness (Geikie,1871, pp.290-4; Harker,1908,p.37). In Rhum the lavas were poured out over an eroded surface of the Western Granophyre and Torridonian sediments.

Harker (1908,pp.37-54) noted that interstratified with one another near the base of the lavas in all five islands (Sanday included) are agglomerates and conglomerates, the presence of the latter suggesting that a great river traversed the lava-plateau in Tertiary times. The pitchstone of the Sgùrr of Eigg has been considered to be either a series of lava-flows extruded in a river-valley (Geikie,1871,pp. 303-9; Bailey,1914), or an intrusive sheet (Harker,1906; 1908,pp.170-5).

Tertiary Central Intrusive Complex of Rhum. The Central Complex of Rhum consists of ultrabasic, basic and acid rocks. A ring-fault bounds the Central Complex on the south and east (Bailey,1944,p.167). The fault has a large throw and "in extreme cases the aggregate uplift registered by certain exposures of Lewisian Gneiss within the ring-fault amounts to 6000 or 7000 feet" (Bailey,1944,p.177).

<u>Tertiary Central Intrusive Complex of Rhum : Ultrabasic Complex and Associated Gabbros.</u> The basic and ultrabasic components (of an estimated total thickness of over 2,000m.) usually have steeply transgressive margins, although Harker (1908,p.68) believed that the ultrabasic rocks were of laccolithic form. Brown (1956) and Wadsworth (1961) considered that bottom-accumulation in a large magma-chamber produced the rhythmic layering in the ultrabasic bodies, and that the complex was later uplifted to its present position inside an almost circular ring-fracture.

Brown (1956,p.3) and Wager and Brown (1968,p.290) considered that the central block, subsequent to its consolidation, was upheaved by between 3,000 and 5,000 feet (ca. 1,000-1,500m.) along the ring-fracture, the movement lubricated by the partly bordering steep gabbroic ring-dyke. Sheet-like and dyke-like masses of eucrite and gabbro within the layered series were injected at much the same time (Brown,1956; Wadsworth,1961). Field-relationships indicate that the uplift of the ultrabasic complex is later than the main ring-fault bounding the whole Central Complex (Stewart, 1965,p.449).

<u>Tertiary Central Intrusive Complex of Rhum : Southern Mountains Complex</u>. Acid igneous rocks in southern Rhum, including tuffs and breccias, lie within an arcuate fracture about 2km. in diameter and entirely within the main ring-fault

(Hughes,1960). This fracture involved subsidence of about 500m. in the east but dying out to the west. Along the fracture steeply dipping felsitic and granophyric masses were injected passing into a central block of Torridonian rocks as sheets. Most of the acid rocks and their associates are older than the emplacement of the ultrabasic complex.

Tertiary Central Intrusive Complex of Rhum : Western Granophyre. This body in north-western Rhum outcrops over 15km^2. The body is faulted against Torridonian to the north, and its eastern margin is truncated steeply against the later ultrabasic complex (Wadsworth,1961). The opinion of Geikie (1897B, vol.2, p.404) and Harker (1908,p.60) was that the granophyre had intruded the basalt lava outlier at Orval. This opinion was seriously questioned by Black (1952B,p.110) who, supporting an even earlier view (Judd,1874,p.254), concluded that the Orval basalts rest unconformably upon the earlier granophyre.

Bailey (1944,p.184) interpreted the Western Granophyre as the filling of a subterranean cauldron-subsidence. Its contact with the basic and ultrabasic rocks is steep and inclined eastwards. On the north, its contact with the Torridonian strata is along a reverse-fault (Hughes et al.,1957, p.338). Black (1954) noted that part of the junction of the largest acid mass in the west of Rhum with the Torridonian rocks is not faulted (although Hughes et al.,1957, were in disagreement), and that there is a transition from micro-granite to granophyre, through to metasomatised Torridonian Sandstone. In consequence, Black believed that the acid rocks and transitional rocks were produced by metasomatic and metamorphic transformation of the Torridonian Sandstone (1954,p.271). More recently, Dunham (1967,pp.346-7) has stated that, because of the degree of thermal metamorphism that has affected the Lewisian rocks around the complex, the acid magma in Rhum was generated by partial fusion of the Lewisian country-rock.

Sequence of Igneous Events in Rhum. On the basis of the work of other authors (summarized above), a tentative sequence of events in Rhum was devised by Stewart (1965,p.450) : (i.) injection of a basic magma into a reservoir within the basement rocks; (ii.) crystallization of this magma producing a layered ultrabasic complex, with accompanying eruption of residual liquids, and with partial melting of the basement producing palingenetic acid magma which was injected upwards; development of the arcuate fracture of the Southern Mountains; (iii.) uplift of the central block along the main ring-fault; (iv.) emplacement of the cone-sheets during further uplift; (v.) emplacement of essentially solid cumulates inside an inner ring-fracture lubricated by the marginal gabbroic magma, and intrusion of gabbroic and eucritic sheets and dykes into the layered rocks and outside their margin;

(vi.) eruption of the lavas of western Rhum.

The alkali-basaltic lavas of western Rhum are certainly of late age and may well have originated from another centre than Rhum since the eruptive equivalents of the residual liquids in stage (ii.) would be of Porphyritic Central type (feldsparphyric dolerite). The absence of such lavas can only point to extensive erosion before the alkaline lavas were erupted.

Tertiary Pluton in Muck. In south-central Muck an olivine-gabbro body (the Camas Mòr Gabbro) has the general habit of a dyke (Harker,1908,pp.96-7). It is less than 100m. in width, and extends in a N.N.W. direction about 2km. Harker believed that it belongs to the plutonic phase, and is not a dyke. Tilley (1947) referred to the Camas Mòr Gabbro as a dyke. The present author has regarded the body as part of a plutonic mass.

Tertiary Sills. The sills of the Small Isles, most prominently displayed in Rhum, are like those of Soay, i.e. concordant and of porphyritic basalt similar to that of the dykes (Harker,1908,pp.162-8).

11:IV. Nomenclature.

The concepts and definitions discussed in Chapter Four are applicable to the present chapter. The total observed dykes in the island of Rhum are sometimes loosely referred to as members of the "Rhum-Swarm". The total observed dykes in the five islands of the Small Isles are sometimes collectively referred to as members of the "Small Isles Swarm".

11:V. Method of Study.

Most of the techniques employed in the analyses of the dykes of the Small Isles are the same as those described in Chapter Five (III).

Nearly one-thousand outcrops of dykes are recorded, and from these, for purposes of analysis, eighteen groups are compiled. Each group consists of 50 dykes, and this figure was chosen because of the low-intensity of the number of dykes, in contrast with for example the dykes of Skye.

Fig.107 shows the location of the centre-spots, and the traverses from which observations are gathered to set up the groups. The small number of recordings (16 outcrops) on Canna and Sanday precludes the compilation of a group. Fig. 139 (Appendix 25) illustrates the locations of all the traverses covered in the Small Isles.

Not all of the analyses are illustrated diagrammatically, although most of those undertaken for the Skye-Swarm are carried out for the dykes of the Small Isles. The data for all analyses is given in Appendices 18 to 24, and referrence should be made where appropriate to fig.107 for purposes of the location of the eighteen groups.

In some respects the compilation of the groups differs from that for the groups of the Skye and Ardnamurchan Swarms, in that a few dykes of possible subswarms, which are generally of different trend to that of the majority of dykes are not excluded. The chief reason for this is to facilitate verification of the possible existence of a radial-swarm. In the analyses of certain functions, removal of data on dykes belonging to a certain subswarm (demonstrated below) is necessary. In all analyses, described in this chapter, indication of exclusion or inclusion of such data is given.

11:VI. Trend of the Dykes.

Fig.108 (no corresponding table given in appendices) shows the arithmetic-average trends of groups of, in most cases, ten dykes. The end of the bar adjacent to the coast is at that locality regarded as the mid-point for each group of ten dykes. The west coast of Rhum, which lies within the margins of the Central Intrusive Complex, was not surveyed for the same reasons that those dykes within the Central Complexes of Skye and Ardnamurchan were not studied. Herein lies the reason for the lack of plots of average trends on this coast.

The average trend of the dykes of the Small Isles is towards N.W. or N.N.W. Certain dykes with N.E. or N.N.E. strike are extracted and made up into groups, mostly of ten dykes, the average trends of which are represented by broken bars (fig.108). A total of about 100 of these are recorded on northern, eastern and southern coasts of Rhum, but they are

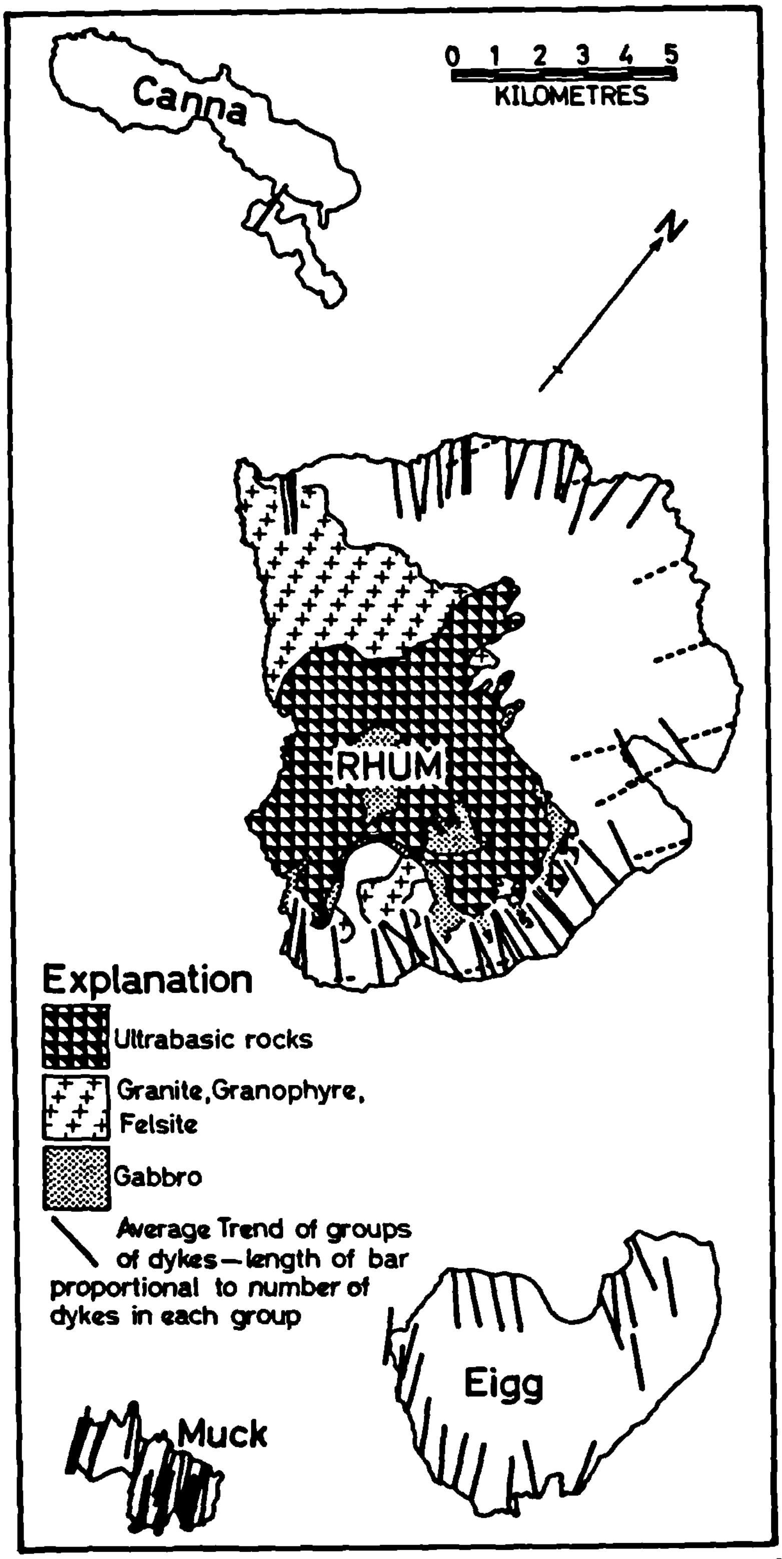


Fig.108. Small Isles Swarm. Average Trends of groups of ten dykes.

most abundant in the traverses on the north-eastern coastal-stretches. The N.E. dykes are henceforth referred to as members of the Rhum-Subswarm.

The average trend of the dykes of Canna and Sanday is northerly, and this is in contrast to that of the dykes of Rhum, as well as to those more regularly north-westerly trends of the dykes of Eigg and Muck. There is some fanning of the average trends from W.N.W. to N.W. on Rhum, with a partial radiate disposition about the Central Complex.

Fig.109 shows the same averages for Rhum with projections along their strike into the area occupied by the Central Complex. This illustrates how very partial is the radiate disposition of the dykes. Intersections of projections are by no means clustered at any one point. Conclusions from fig.110, constructed on a different basis, are the same. The computation of average trends for groups of ten dykes, and the use only of trends of dykes observed to be regular over long distances, are two ways of ensuring minimal error of deduction from such maps as figs. 109 and 110.

A detailed analysis of the frequency-distribution of the trends in groups of 50 dykes is given in Appendix 18. Most of the groups display a broad spread of trend with no definite maximum. Groups on Eigg, and more especially on Muck, approach Gaussian-Distribution, with much narrower spreads of trend, and with pronounced maxima within the in-

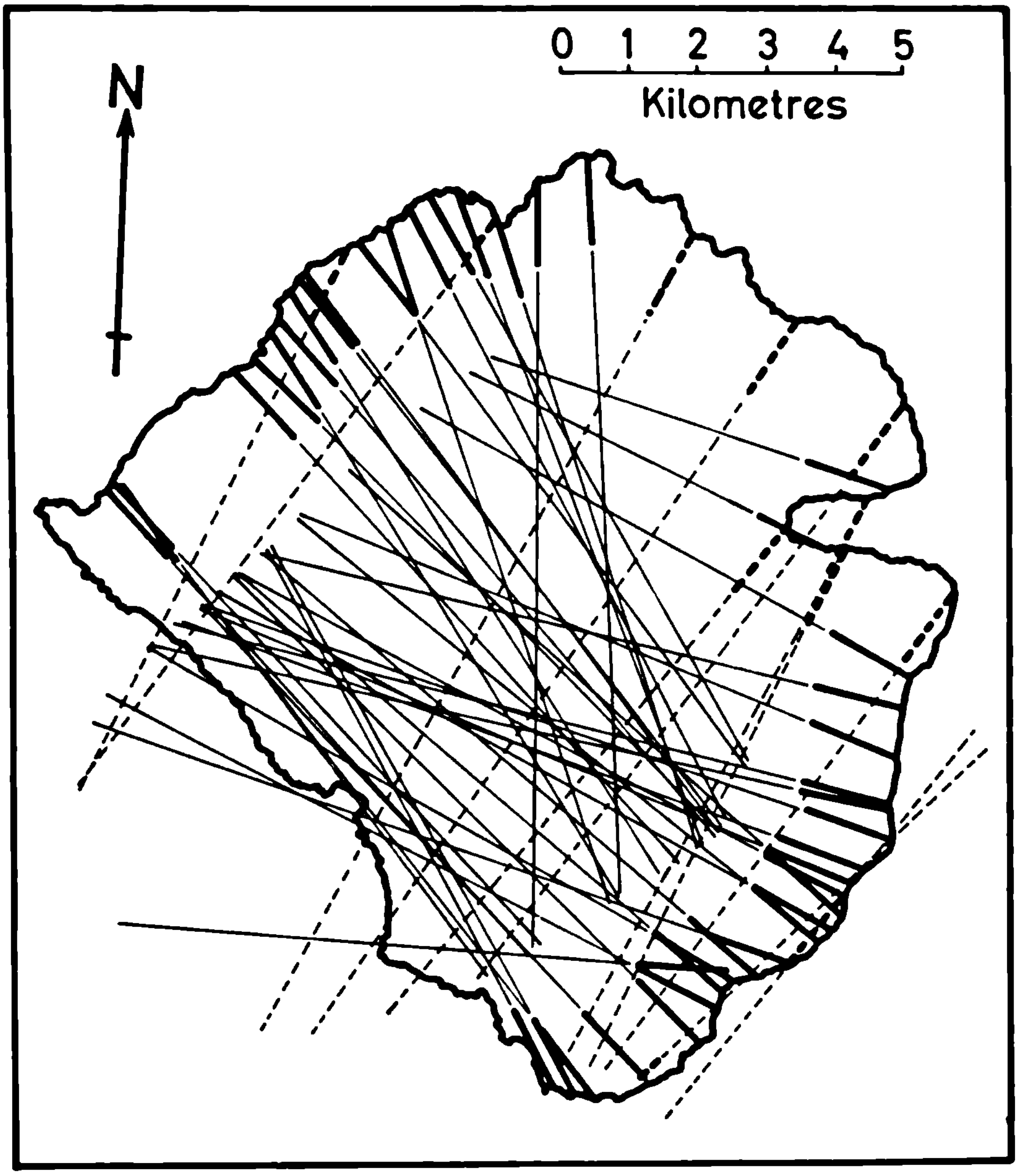


Fig.109. DYKES of RHUM. Projections of Average Trends of groups of ten dykes.

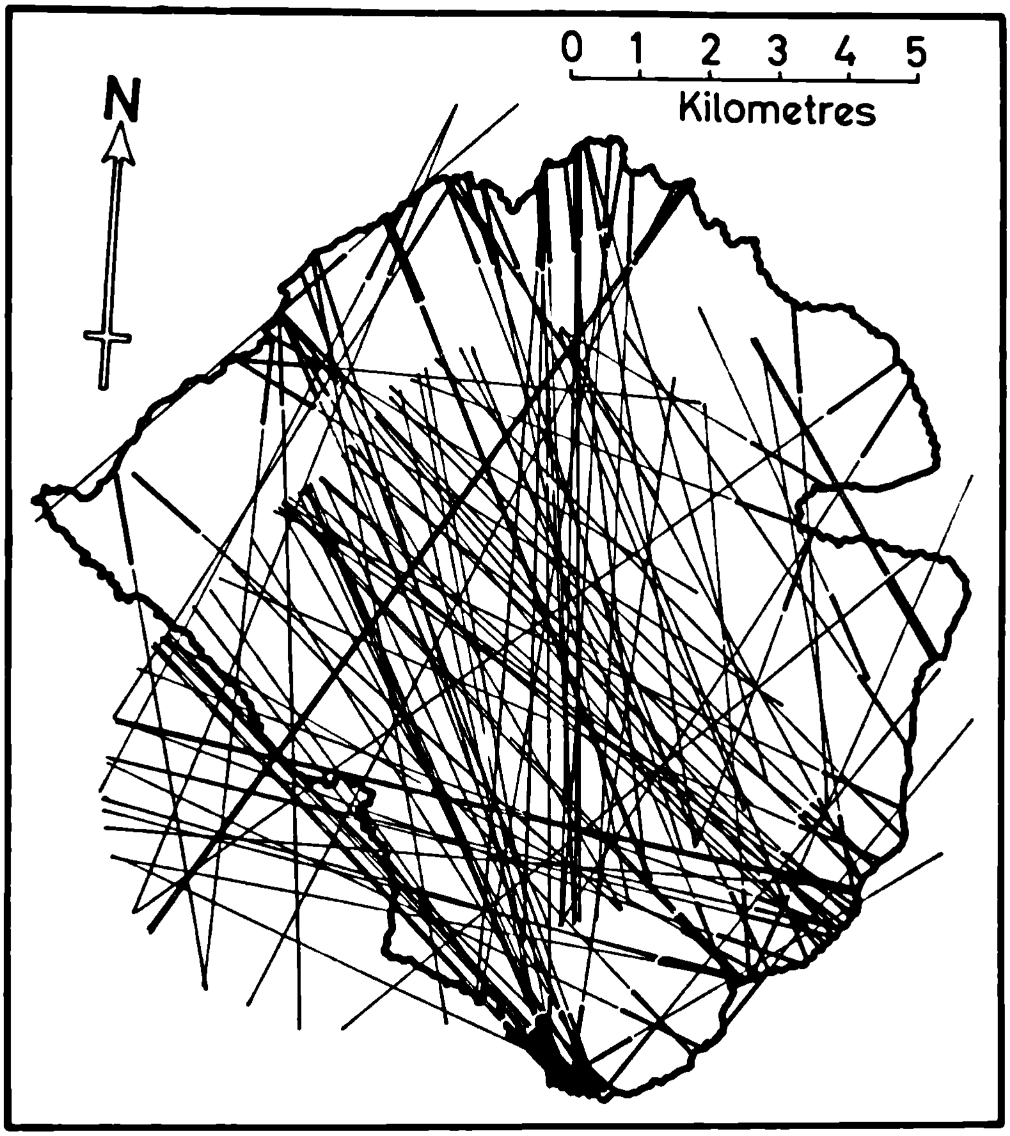


Fig. 110. DYKES of RHUM. Projection of dykes which were seen to have twenty or more metres of regular trend.

terval 315 to 339 deg. of compass, except for group 'EA' in which the maximum is more westerly at 300 to 309 deg. of compass. The shift in the trend from 'RA' through to 'RJ' can also be studied in detail in the group-analyses.

Certain of the values, falling within the 10-deg. intervals in the group-analyses of Appendix 18, are in parentheses (round brackets except in group 'RF'). These correspond to dykes whose trends — considered in relation to the geographical location of each individual dyke — are extraneous to thòse of the majority of dykes within each group, and most of these belong to the Rhum-Subswarm. (A single bracket adjacent to a number, e.g. in group 'RD', indicates that half of that number are considered to belong to the subswarm.)

In Appendix 19, these extraneous dykes are individually named by their field-codes. Group 'RF' is split into three sets (Appendix 18) : (i.) westerly dykes (round brackets), (ii.) N.N.E. dykes (Rhum-Subswarm ... square brackets), and (iii.) three extraneous N.W. dykes. These last are the named dykes, and the first two sets are analysed separately, in Appendix 19.

The arithmetic-mean, the median, and geometric-mean trends for the groups are given in Appendix 19, with dykes of the Rhum-Subswarm excluded. Arithmetic-mean and median sometimes do and sometimes do not lie within the 10-deg. geometric-mean. These are indicated respectively as typical of "normal" ('N') and "abnormal" ('A') frequency-distributions. There appears to be little regularity to the geographical distribution of 'N' and 'A' groups, except that groups on Eigg and Muck are mostly "normal", and those groups on these islands that are "abnormal" are shown by the data to be little-removed from "normal". This corresponds to the findings in the Skye-Swarm, where "normal-distributions" are frequently found among groups of dykes intruded into the lava-pile.

The standard-deviation of the trend is represented by the contour-map of fig.111, based on group-analyses (Appendix 19). (Again, dykes of the Rhum-Subswarm are excluded from computations of this function.) High standard-deviation is characteristic of north-western, north-eastern, and south-eastern districts of Rhum, with intervening regions of lower deviation. The trends of the dykes on most of Eigg and on Muck exhibit relatively low standard-deviations.

The analyses of the trends of all of the dykes of the Small Isles, by number and by summated thickness, show a close correspondence (fig.112a; Appendix 20). The frequency-distribution, however, is very irregular in form (cf. the Skye-Swarm, fig.15), although a pronounced maximum is developed near N.W. trends. The distribution is by no means Gaussian, and the abundance of trends towards W. and W.N.W. produces an asymmetry.

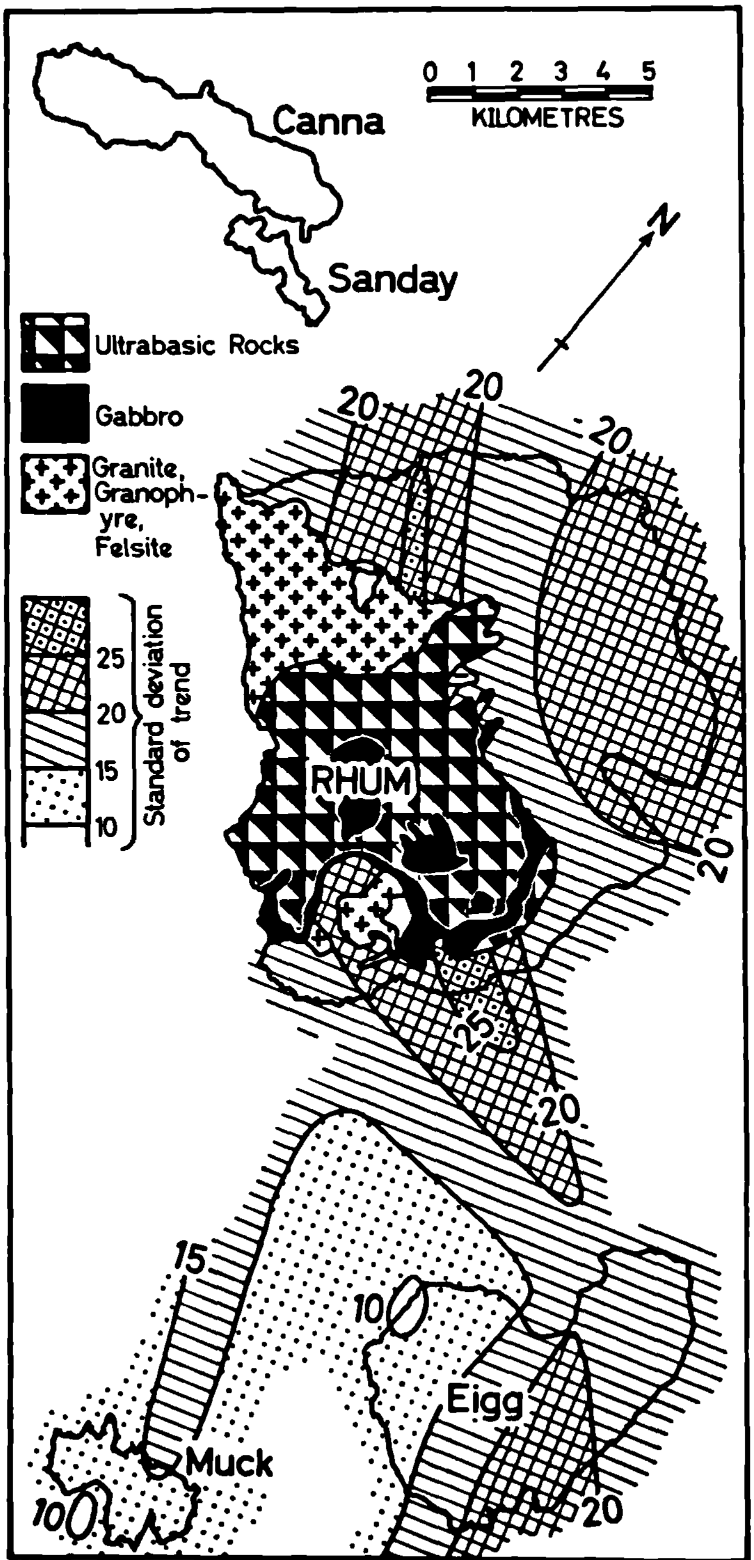


Fig. 111. Small Isles Swarm. Standard deviation (10 degree interval) of trend of dykes.

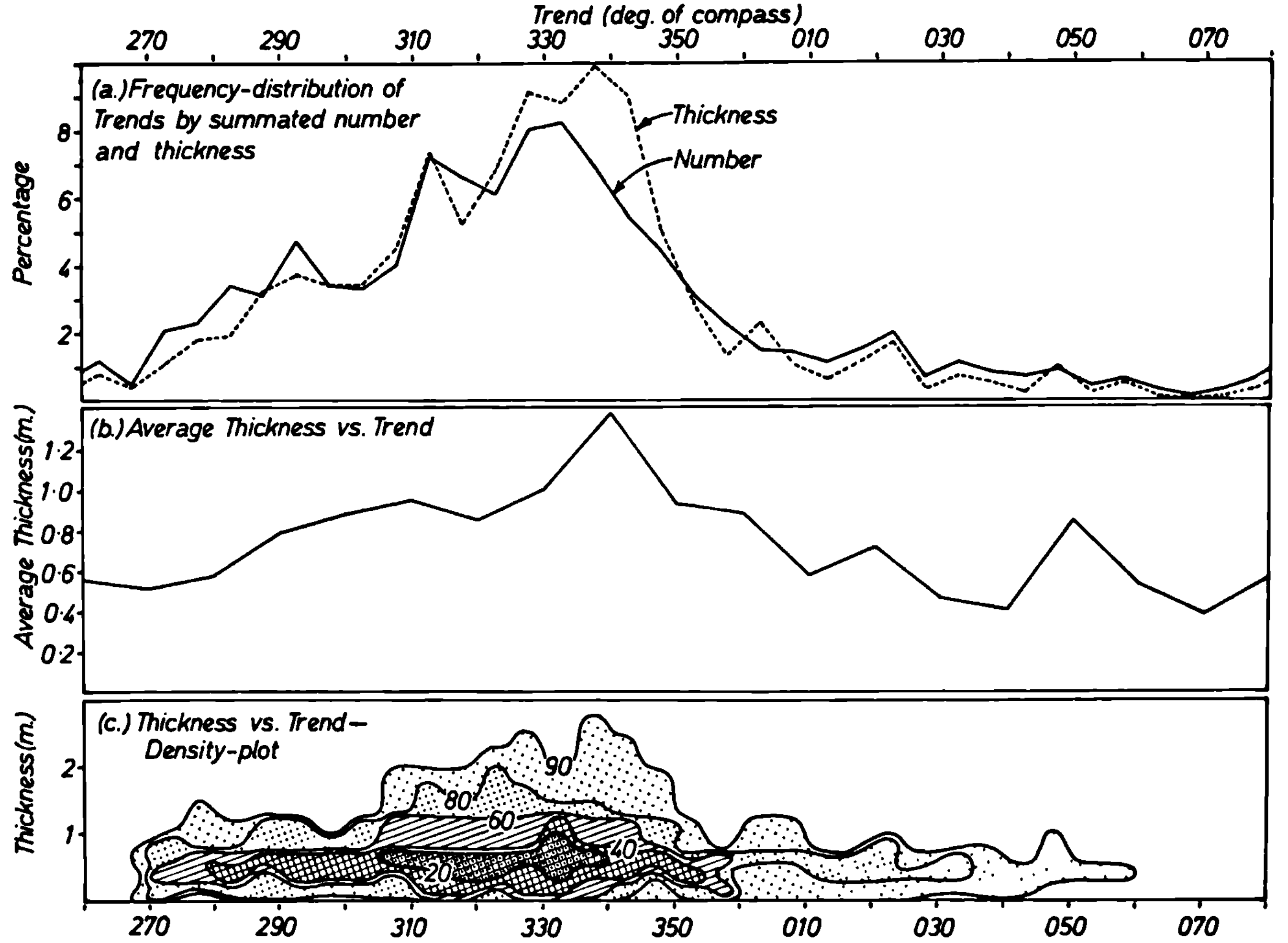


Fig. 112. Dykes of The Small Isles. Some properties of their trends.

Analyses of the trends of the dykes on Rhum, Eigg, and Muck, separately, by the same method, however, reveal that the trends on Eigg and Muck are distributed symmetrically about definite maxima, viz. 305 to 329 deg. of compass for Eigg and 325 to 344 deg. of compass for Muck (fig.113b. & c.; Appendix 21). The distribution of the trends of dykes on Rhum, on the other hand, is very irregular (fig.113a.). (The data includes dykes of the Rhum-Subswarm.)

Little "control" of the trend of the dykes, by pre-existing structures in the country-rock, is observed in the Small Isles. This contrasts, especially in the case of the Torridonian country-rock, with findings within the Skye-Swarm, although, as it was pointed out in Chapter Six (VI), coincidence of a dyke with a strike-slip joint in Raasay and Soay could be a chance circumstance.

It was also mentioned in Chapter Six (IV) that certain dykes outcropping in the Torridonian country-rock of Soay may represent a northward extension of the Rhum-Subswarm. Eleven dykes in Soay are of a trend uncommon to that of the majority of dykes on the island. These trends are 27, 19, 21, 22, 28, 22, 26, 28, 22, 17, 42 deg. of compass, averaging at 25 deg.

11:VII. Dilation of the Dykes.

A method using a variable length of section, similar to that described for the analysis of the Skye and Ardnam-

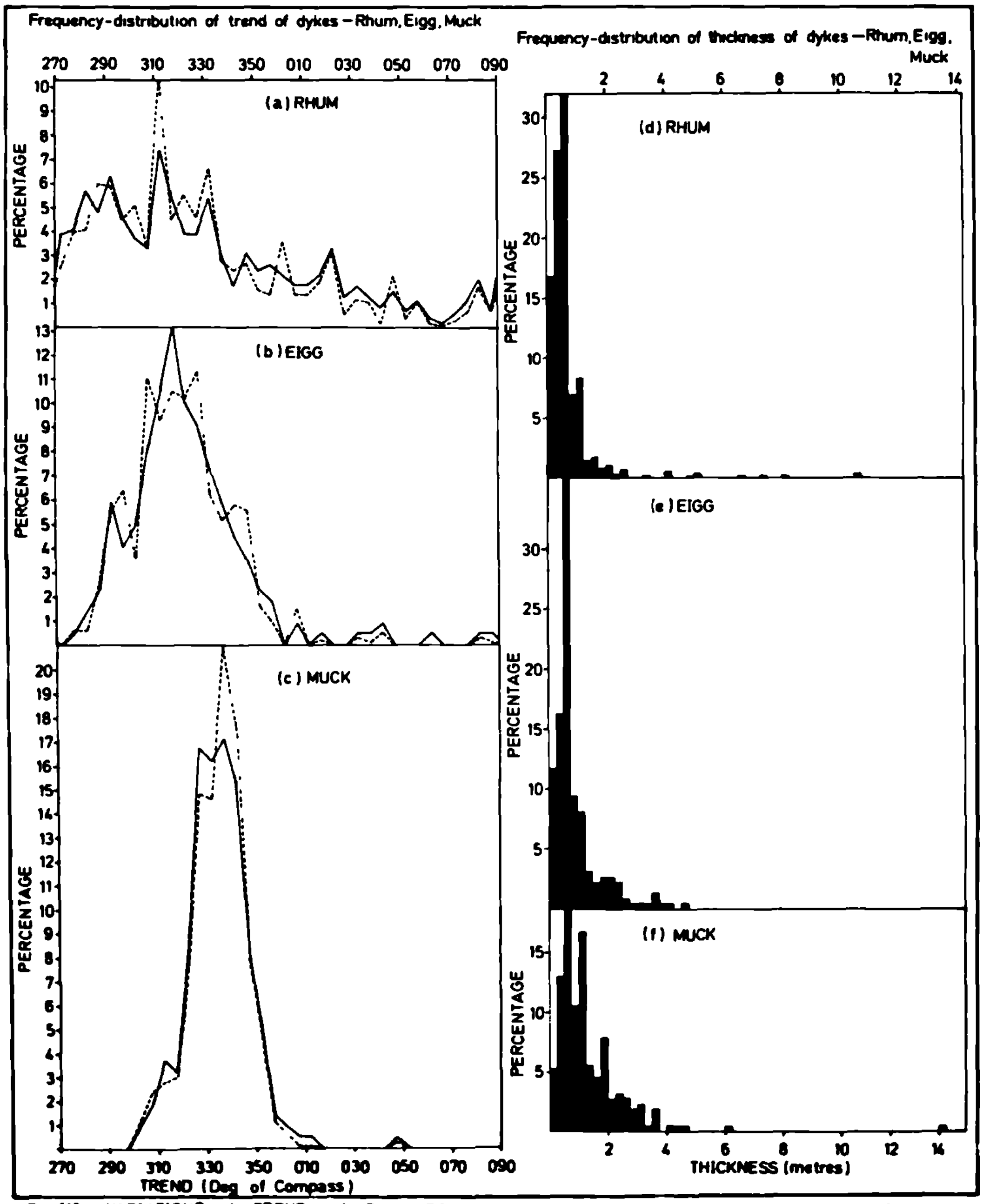


Fig.113. VARIATIONS of TREND and THICKNESS of dykes on RHUM, EIGG and MUCK (Small Isles)

urchan Swarms, is adopted for the Small Isles Swarm. One major dissimilarity is that the length of each section is measured along that component-direction which lies at right-angles to the arithmetic-average trend of the dykes within the section (Appendix 22), despite the low numbers of dykes in certain sections.

The average trends in Rhum are of such great variation that the above is considered a necessary adjustment to the method previously employed. For the sake of simplicity, the same procedure is used throughout the Small Isles. One notable advantage of this adjustment is that the existence of a radial-swarm can be more easily verified or nullified.

Fig.114 (in pocket) is based on 47 sections (Appendix 22), of total length about 50km., and containing 856 dykes, excluding the sections on the north coast of Ardnamurchan (Appendix 9A). The intensity of the crustal-extension is geographically very variable, but certain regions of high-intensity are easily discerned. (Fig.48 shows the locations of the axes of dilation in the Small Isles. These are based on an interpretation of fig.114.)

On the north-western and south-eastern coasts of Rhum, relatively high values of dilation are found. On tracing the contours from the south-eastern coast of Rhum to Eigg, a very definite N.W. axis is seen to pass through the Bay of Laig. Tracing of contours from the north-western coast of

Rhum towards N.W. is hindered by lack of exposures.

A 3 per cent. contour passes from the southern coast of Rhum to meet the eastern shores of Eigg, and this marks an axis of somewhat lesser importance. This is separated, by a prominent region of low-intensity extending from Rhum to between Muck and Eigg, from the N.W. to S.E. region of high-intensities extending from the north coast of Ardnamurchan, through Muck, and apparently through to the north-western coast of Rhum and to Canna. The contours to the west of Rhum are highly conjectural, if only because of the indeterminate extent of the Central Intrusive Complex in this direction. The contours are intended to indicate the possible dilation-values, if the Complex has a small extent to the west.

It appears that the high-intensities on the extreme north-west of Rhum have little in the manner of a counterpart on the south coast of the island, except in so far as they reflect the northward extension of the region of high-intensity passing through Muck, and just touching the extreme south coast of Rhum.

The high-intensities on Muck suggest that a body of Central-Intrusive type is located at some depth below the present level of erosion, off the south coast of the island. Indeed, the presence of the Camas Mòr Gabbro in south-central Muck is in part a corroboration of this hypothesis.

The Rhum-Subswarm, with its axis trending towards N.E. through Loch Scresort, creates a maximum observed dilation of only one per cent. The dykes of 25 deg. average trend on Soay (mentioned in the previous section of this chapter) have an aggregate-thickness of about 10m. They occur in a traverse of about 3km. (E. to W.), giving a dilation of one-third per cent. This is in accord with their rôle as members of the Rhum-Subswarm.

In the Small Isles, the axes of dilation (fig.48) and the distribution of the dilation-contours in general (fig. 108) are characteristic of a linear-swarm of dykes. Little tendency towards the characteristics of a radial-swarm is evident. The linearity of the swarm is especially well demonstrated by the very low dilation-values on the north coast of Loch Scresort and on the north-east coast of Rhum.

Axis 6 of fig.48 trends in a straight line from north-eastern Rhum, through Muck, to Ardnamurchan, and projects to meet axis 6B on the south coast of Ardnamurchan. Hence, the dykes on Muck lie on the same axis as those dykes in the Ardnamurchan Peninsula (Ardnamurchan-Swarm). Since their intensities are very high (see also the section below on number of dykes), it may be said of the dykes on Muck that some are members of the Ardnamurchan-Swarm. On the other hand, some of the dykes on the north coast of Ardnamurchan may be members of a "Muck-Swarm", which "centres" somewhere to the south-east of the Island of Muck.

In this respect, the term, "Small Isles Swarm", is somewhat of a misnomer. Especially in Muck, less so in Ardnamurchan, and perhaps also to some extent in parts of Rhum, and in Canna, the dykes are of a conglomeration of swarms. The Ardnamurchan Linear-Swarm, the Rhum-Swarm, and the linear-swarm which extends from Muck are the obvious contributors to this mixture. The possibility, that a few of the dykes of the Rhum-Subswarm and those in Canna and Sanday stem from the Skye-Swarm, also cannot be entirely denied.

11:VIII. Numbers of the Dykes.

With certain exceptions, the intensity of distribution of the dykes by number per kilometre (fig.115) is of the same pattern as the dilation-map. The Rhum-Subswarm (contours indicated by a thick broken line) is equally well displayed on both contour-maps. Moreover, in the main N.W. swarm, the belts of high-intensity, extending from the south coast of Rhum towards Eigg and Muck, are remarkably similar on the two maps. One notable exception is the displacement of the axial region on the north coast of Muck towards the east, with a corresponding relatively low-intensity on the west. However, the location of the highest intensity on Muck remains the same.

Fig.115 is constructed using the same sections as for fig.114 (Appendix 22). Some restraint has been exercised

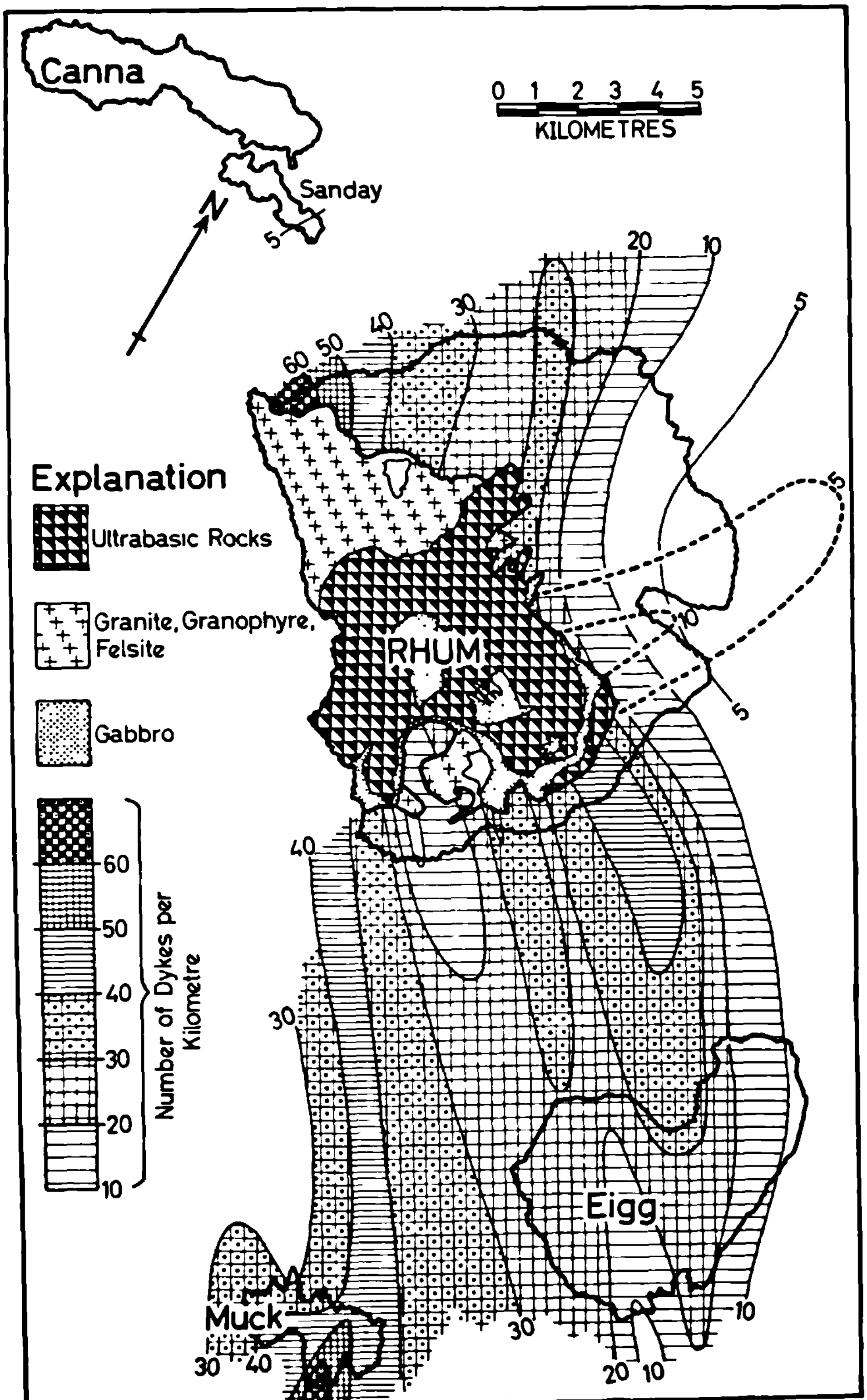


Fig. 115. Small Isles Swarm. Intensity of dykes — Number of dykes per kilometre

in projecting the contours of number of dykes per km. in areas both off the east coast of Rhum and between Rhum and Canna. The reason for this is the unusual configuration of the distribution of numbers in northern Rhum. The major axis of dilation on the north-west coast of Rhum (axis 5A of fig.48) is not paralleled by a similar axis of number of dykes per km. It may well be that such an axis is obscured by the progressive increase from 30 d.p.k. to over 60 d.p.k. along this section of coast.

A minor, N.N.W.-trending axis of number of dykes is developed at Kilmory (fig.114, for location), to the east of the position of dilation-axis 5A. This has its counterpart in a slight deviation of the dilation-contours at the same location (fig.114). Otherwise, correlation of the intensity of the number of dykes per km., between regions to the south and south-east of the Central Complex of Rhum and regions to the north and north-west, is very poor.

The relationship between the value of 60 d.p.k. in the north-west of Rhum and the value of 5 d.p.k. on Sanday, and even lesser intensity on Canna, is even more problematic. In this particular case, it appears that the obvious solution is that the lavas on Canna are of very late-age, and overlie a N.W.-trending dyke-swarm of earlier age. There is some confirmation of this to be found in the contrast between the northerly trends of the dykes of Canna and Sanday, which would be later intrusions, and the north-westerly trends of those on Rhum, which would be of earlier age. If this solution is correct, it is clear that the dilation-contours of fig.114 are in error. Undoubtedly, the rate of decrease of dilation to the north-west of the Central Complex is unusually high, and contrasts sharply with the rate of decrease away from the Central Complex to the south-east.

In fig.115, the connexion of continuous contours from Muck, through the south of Rhum, along the area off the east coast, to meet the north coast of Rhum, is hampered by the lack of suitable exposure off the east coast. It seems possible that the value of over 60 d.p.k. on the north-eastern coast represents the position of an axis, and that a similar connexion of contours can be made as in fig.114. Yet, it is now obvious that, though Canna may be on the line of this axis, here the dyke-swarm is "buried", and the dilation-contours between Rhum and Canna, though of correct orientation, may be of too low a value. It is not then inconceivable that this particular branch of the swarm extends to North Uist.

The distribution of multiple-dykes, throughout the Small Isles Swarm, is comparatively irregular and corresponds but little to the pattern shown by the Skye-Swarm.

Groups on Rhum (Appendix 19 : dykes of Rhum-Subswarm included) have extremely low proportions of multiple-dykes, except in the extreme north-east (group 'RA') and south of Loch Scresort ('RF'). This is in contrast to Skye, where groups near the Central Complex have high percentages of multiple-intrusions.

In Eigg, on the northern and eastern coastal sections, numbers of multiple-dykes are again extremely low, but they increase appreciably in groups 'EC' and 'ED', on the south and south-west sections. Muck is exceptional, in comparison with the other islands, in that its groups have moderately high proportions of multiple-dykes, except in the south-east ('MD'). In Ardnamurchan, on the other hand, multiple-dykes are again sparsely distributed (Appendix 10).

By direct analogy with the Skye-Swarm, such evidence, as the relatively high proportions of multiple-dykes in Muck and in the more closely adjacent sections of Eigg, points again towards the probable existence of some Central Intrusive body in the vicinity of Muck.

Once again, the phenomenon of "grouping" is not quantitatively analysed. It is not as well developed as in the Skye-Swarm, although it is displayed to a minor extent in sections on Rhum near the dilation-axes, and also within the dykes of Muck.

11:IX. Thickness of the Dykes.

A detailed analysis of the frequency-distribution of the thickness, in the eighteen groups, is given in Appendix 23 (dykes of Rhum-Subswarm included). In all of the groups there are very many dykes of thickness less than one-metre, especially on Rhum. The overall arithmetic-average thickness of the total number of dykes observed in the Small Isles is 0.90m. (Appendix 20). The broader dykes are confined chiefly to the groups of south-eastern and southern Rhum.

The spread of the thicknesses is very much greater in Eigg and, more especially, Muck. The arithmetic-mean thickness of the groups (Rhum-Subswarm not excluded) is generally low in groups on Rhum, and it increases in groups on Eigg and Muck. Median and geometric-mean thicknesses are also shown in Appendix 23, and the correspondence between the arithmetic- and geometric-means and the median is indicated as being of the "normal" or "abnormal" type of distribution (Ch.9:II). There is little regularity of pattern in the distribution (geographically) of these two types, although most of the dykes on Eigg appear to be of the "normal" kind.

Arithmetic-average thicknesses of the groups (with members of the Rhum-Subswarm excluded) are also given in Appendix 19. There is a fairly close correspondence between the values with and the values without this exclusion, and dykes of the subswarm are generally of the same range of thicknesses as the dykes of the main linear-swarm in the same areas.

The frequency-distribution of the thickness (Appendix 24) for all of the dykes of the Small Isles Swarm (Rhum-Subswarm included) is illustrated in fig.116. In most respects, this corresponds closely to the frequency-distribution for the Skye-Swarm (fig.75), with a large number of dykes of less than 2-m. thickness, and proportionately fewer dykes of greater thickness.

Similar frequency-distributions (with dykes of the Rhum-Subswarm included) are plotted for the individual islands (fig.113 d.,e.,f; Appendix 21). These histograms demonstrate that most of the thicker dykes, except for a few on Muck, are restricted to Rhum. Eigg has a higher, and Muck an even higher, proportion of dykes between 1- and 4-m. thickness.

The relationship of the trend of the dykes to the thickness (fig.112 b. & c.) is illustrated in the same manner as in figs.76 and 77, for the Skye-Swarm. The arithmetic-average thickness of the dykes (including the Rhum-Subswarm), calculated for 10-deg. intervals of trend (Appendix 20, using the 275 to 284 deg., etc., rather than the 270 to 279 deg., etc., range), is shown in fig.112b. Unlike the corresponding plot for the Skye-Swarm (fig.76), the maximum average thickness lies at 340 deg. of compass (Skye-Swarm, at 10 deg.), and is of a very much lower value. Moreover, the peak is not as distinctly developed.

Similarly, the trend vs. thickness density-plot (fig.

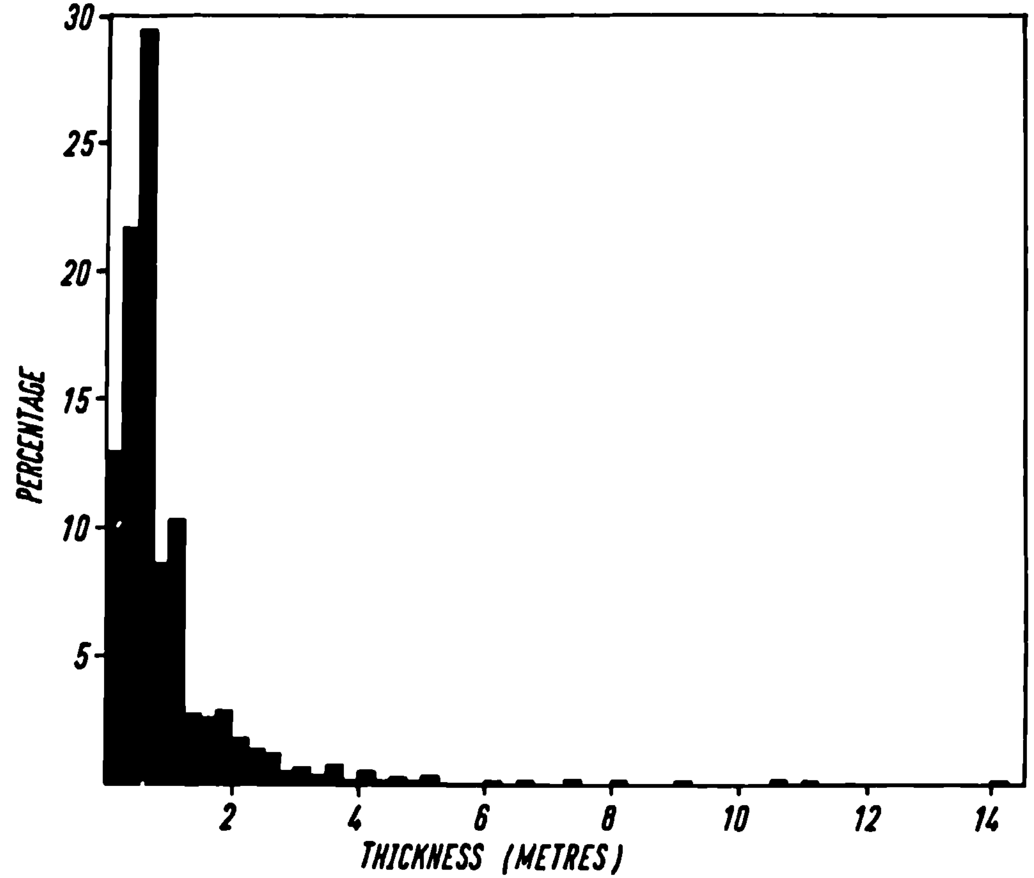


Fig.116. Frequency-distribution of Thickness for Small Isles Swarm

112c. — 20 per cent. intervals, only, plotted; Appendix 24) of the dykes of the Small Isles (including the Rhum-Subswarm) differs from the same plot for the Skye-Swarm (fig.77). The spread, especially towards the westerly trends, is much more marked, and the spread of the thickness is much less pronounced, for the Small Isles Swarm.

11:X. Dip of the Dykes.

Appendix 18 shows the group-analyses of the dip of all the dykes of the Small Isles (including the Rhum-Subswarm). Generally, in groups on Rhum, there are marginally more dykes dipping towards S.W. than towards N.E. The converse is true of the dykes of Eigg and Muck, and this bears some relation to the westerly-dip of the lavas on these islands. The proportion of vertical dykes, too, is markedly greater on Eigg and Muck than on Rhum. Conversely, the spread of the dips is greater within groups on Rhum than within groups on Eigg and Muck.

The mid-point cotangent dip of the dykes for the groups (including dykes of the Rhum-Subswarm) is shown in Appendix 19. The average dips for groups on Eigg and Muck are towards N.E., or very slightly inclined towards S.W. The average dips on Rhum are towards N.E. in north-western areas, and towards S.W. in all other districts.

Exceptionally low average dips towards N.E. are found in groups 'RA' (north-western Rhum), and 'EA' and 'EB' (northern and southern Eigg). Exceptionally low average dips towards S.W. are found in groups 'RD' (northern Rhum), and 'RH' and 'RI' (south-eastern Rhum, near the axes of dilation). The change from a predominance of S.W. dips to one of N.E. dips, in passing from groups in the south of Rhum, to groups on Eigg and Muck, is worthy of note.

Finally, in the same manner as sections across the Skye and Ardnamurchan Swarms (figs.101, 102, 105) were drawn to show the dips of dykes taken from an area, figs.117 and 118 illustrate the changes in dips of the dykes in passing from the W.S.W. to E.N.E. across south-eastern Rhum, and Muck and Eigg. The plots for the dykes of Rhum (larger open circle, fig.118) are distinguished from those of Muck and Eigg (smaller black circle). The dykes of Rhum have a greater spread of dip, with equal proportions of N.E., to S.W., to vertically dipping, dykes. The dykes of Eigg and Muck have proportionately more vertical members, and a predominance of N.E. over S.W. dips. There is, however, not the significant change in dips across the swarm as seen in parts of northern Skye.

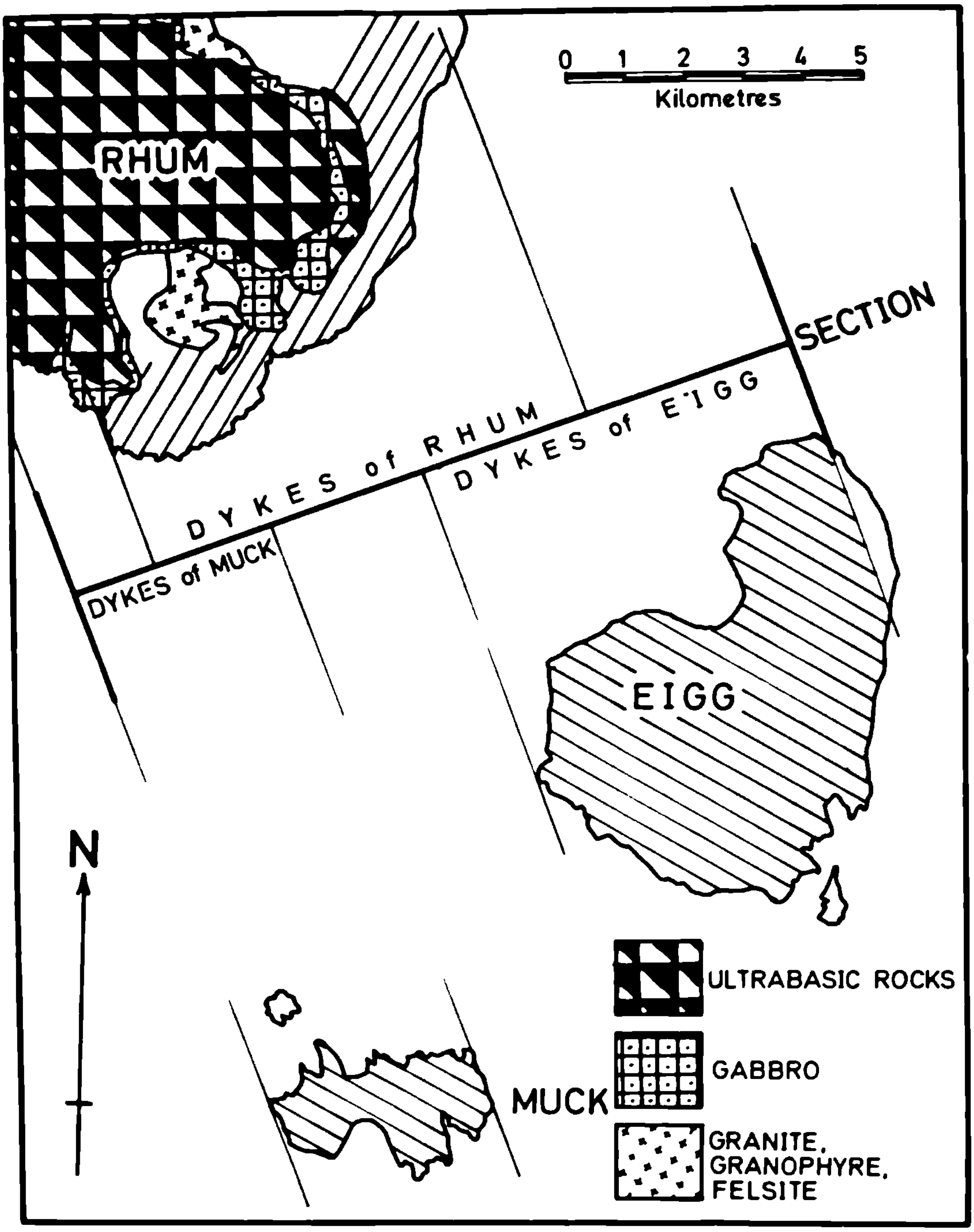


Fig.117. Location of section for the graphical analysis of the dips of the dykes of Eigg, Muck, and S.E. Rhum.

(Diagonal lines indicate N.NW-S.S.E strip-areas, along traverses within which there are recordings of dykes)

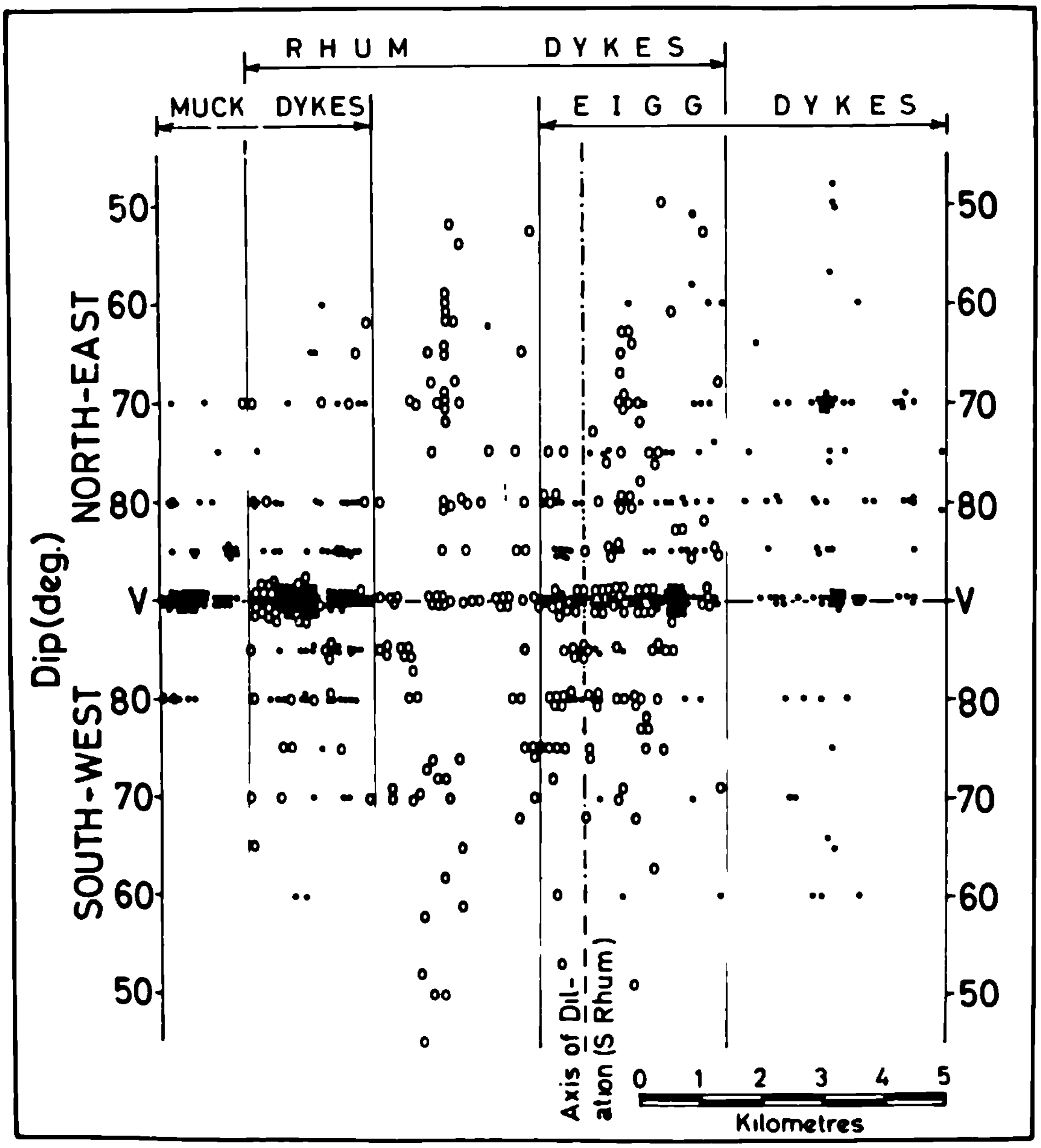


Fig.118. Graphical analysis of the dips of the dykes of Eigg, Muck, and S.E. Rhum.

Chapter Twelve

GEOPHYSICAL EVIDENCE
RELATING TO THE STRUCTURE OF THE DYKE-SWARMS

12:I. Introduction.

Evidence which is at present available, and which is relevant to a study of the form and structure of the Tertiary dyke-swarms of Skye, Ardnamurchan and the Small Isles, is discussed under four heads : Magnetic Anomalies, Gravity Anomalies, Palaeomagnetic Evidence, and Radiometric Dates.

12:II. Magnetic Anomalies.

The aeromagnetic maps (Sheets 10, 11, & 12), published by the Ordnance Survey for the Institute of Geological Sciences, show certain illuminating distribution-patterns of magnetic anomalies within the Area of Study. It is believed that many of these patterns can be correlated with the geographical distribution of the dykes in the area.

The contours depicted on the aforementioned sheets represent the total force magnetic anomalies. A proportion of these contours are selected for the construction of fig. 119. No distinction is made on this sketch-map between positive and negative anomalies, and the contours are by no means at equal intervals. Emphasis is made of the trends of the contours in some districts by inclusion of more contour-lines than in other districts.

To further facilitate the analysis of the relation between the trends of the magnetic anomalies and the distribution of the dykes, the axes of dilation are superimposed. These are as in fig.48, except that the Rhum-Subswarm axis

Fig.119. Area of Study... Selected total force magnetic anomaly contours from Aeromagnetic maps. Dilation-axes superimposed.

is extended to Soay. The axes of the Mull-Swarm are also shown in more detail than previously, and their locations are due to the work of Sloan (1970,pp.39-44).

In the neighbourhood of the Central Complexes of Skye, Rhum, Ardnamurchan, and Mull (only part of the last area shown on fig.119), the magnetic anomalies are disposed roughly concentrically about their outcrops. Extremely high maximum negative anomalies are found over parts of all four complexes, and the rates of change of values (gradient) are very great in their vicinity.

Along belts where dykes are very intense, the trends of the magnetic anomalies often approach parallelism with the trends of those dykes and with the axes of dilation. This is especially clearly illustrated along the main dilation-axis and its branches extending from Strathaird as far south as Sunart.

In terraims occupied by the lava-pile, viz. northern Skye, Canna, Eigg, Muck, Morvern, and northern Mull, the contours of the magnetic anomalies show more variable trends and gradients. The rocks of the basaltic lava-pile are susceptible to the acquisition during cooling of high magnetization. The remanent magnetization of the lava-pile somewhat obscures that of the dykes, although the north-westerly trends of the contours are still predominant, especially near Vaternish. This is in marked contrast to the N.E. to

S.W. trend of the anomalies to the west of central Skye, and to the variably-trending contours between Skye and Harris, north of Rona. These latter must be indicative of the magnetization of pre-Tertiary rocks.

No swings of the contours to parallel the axes of the Glenbrittle- and Scalpay-Subswarms are evident. This is explained by (i.) the low-intensities of the dykes, and (ii.) their proximity to the Central Intrusive Complex of Skye, the magnetic anomalies over which mask those of the subswarms. The Rhum-Subswarm, again of low-intensity, is not picked out by the contours, which between Skye and Rhum trend E. to W., and are tangential to both Central Complexes.

However, in the region occupied by the Scalpay Secondary-Swarm, the anomalies are subparallel to the dilation-axis. The anomalies close to the axial-line of the Broadford Bay-Applecross Subswarm, in the Applecross region, trend N. to S. in parallelism with the dykes. The axes of the peripheral folds in the Mesozoic and Cambrian strata, between Broadford and Rubha Suisnish, are also distinguished by a corresponding orientation of the contours of the magnetic anomaly. Perhaps this orientation is further accentuated by the denser distribution of the dykes in these beds. Between Broadford Bay and the Crowlin Islands, it appears that the Scalpay Secondary-Swarm is the dominant feature, and the anomalies due to the subswarms in this district are obscured.

Some north-westerly oriented contours lie between Eigg and Muck and extend to Ardnamurchan. Elsewhere in the Small Isles the magnetic effect of the Rhum Central Complex is paramount.

In Mull and Morvern, the lavas have a control over the form of the contours of the magnetic anomaly similar to that of northern Skye, although again north-westerly trends predominate. In eastern Ardnamurchan, a N. to S. trend of the contours is developed. This parallels the trend of some of the dykes of this region.

The dilation-axis extending from Morar to Loch Linnhe is less well accompanied by parallel contours at its southerly extension into Sunart and Kingairloch. The contours are of pronounced north-easterly trend in Loch Linnhe, and they lie along the same direction as the Great Glen Fault. The N. to S. trends of the contours in Morar, Moidart, and northern Sunart, are parallel to the strike of the foliation of the Moine rocks. It is difficult to say exactly how much of this parallelism is due to the magnetization of the dykes and how much is due to the magnetic properties of the Moinian rocks. This applies not only to the Morar to Loch Linnhe axis of dilation but also to the main axes farther to the west. Evidence in Sleat, however, where the dykes intrude Torridonian and Lewisian rocks, seems to indicate that the dykes here have a greater effect. Being basaltic and thus much more easily magnetized than the psammites and pelites of the Moine Series, it is to be expected that the dykes will produce a similarly greater effect on the mainland.

In passing, it may also be stated that the Tertiary dyke-swarms extending through Islay-Jura and to the south-east of Mull are exceptionally well picked out by the orientation of the contours on the maps of the aeromagnetic anomalies. The older dykes (e.g. of Permo-Carboniferous age), outcropping on the mainland in the Area of Study, are not at all well distinguished by an orientation of the aeromagnetic contours parallel to their trends.

In Lewis, a marked N.W. to S.E. alignment of the anomalies is again found. This orientation can be discerned along a belt extending from the north-west coast of the island almost as far to the south-east as Loch Torridon. The interpretation of this phenomenon is problematic. Dykes of N.W. trend outcrop in Lewis. About 80 N.N.W. or N.W. basic dykes of probable Tertiary age were mapped by Jehu and Craig (1934,pp.867-8). By analogy with other dyke-swarms of the Hebrides, a hypothesis that a deeply-buried latent centre of Tertiary age (some plutonic body, probably of basic composition) exists off the north-west coast of Lewis, is offered in explanation. Dykes of a N.W. regional linear-swarm constitute a higher level (present surface) expression of the deeper igneous structures. These dykes are assumed to be distributed such that decreasing intensities are found to the south-east, where, off Loch Torridon, it is supposed that they merge into the Broadford Bay- Applecross Subswarm.

Such a latent centre, like the one later postulated (Ch.13:III; 16:VI,a; 16:IX) for the Islay-Jura Swarm off the north-east coast of Islay, would lie on that same approximately N. to S. line which connects the Tertiary Igneous Central Complexes.

Fig.120 (derived from the same aeromagnetic maps as fig.119) shows the areal-extent of positive (lined) and negative (blank) anomalies. Areas characterized by very high negative anomalies (over 800 gammas) are shown black, and these occur at the sites of the gabbroic and ultrabasic intrusions of the Central Complexes.

The areas where surface-outcrops are of Lewisian, Moinian, Dalradian, Cambrian, and Mesozoic rocks, are characterized by positive anomalies. The same applies to the Tertiary and Caledonian granites. There are exceptions to these very general statements, notably in the negative anomalies in the Knoydart and Glenelg districts, where Lewisian and Moinian rocks crop out.

The Torridonian rocks, the Tertiary lavas, and the

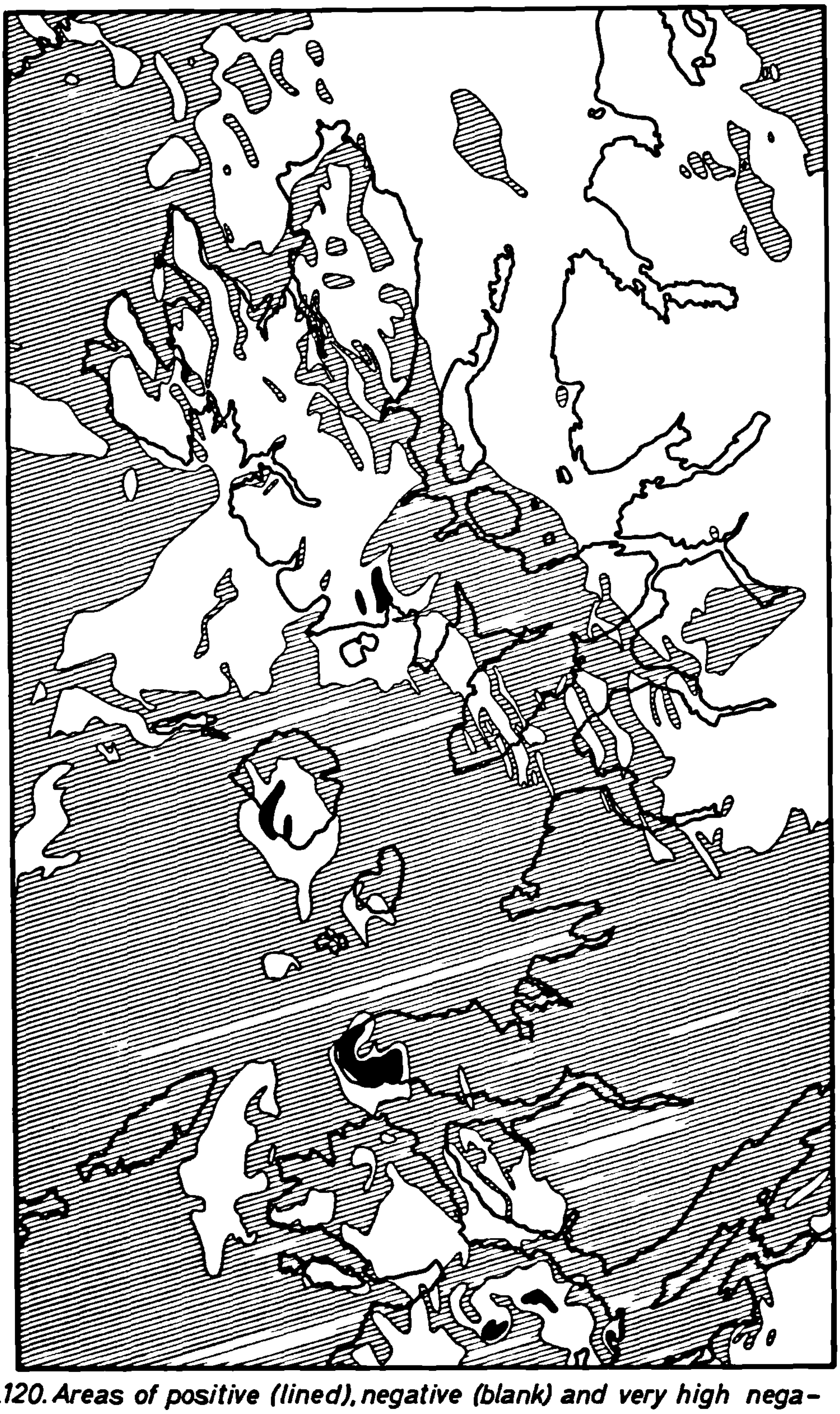


Fig.120. Areas of positive (lined), negative (blank) and very high negative (black) total force magnetic anomalies in the Area of Study. (From Aeromagnetic Maps 10,11,12, I.G.S.)

basic igneous rocks of the Central Complexes are in a general manner characterized by negative anomalies. It is notable that these anomalies do not persist in their negative character along the belt occupied by the dyke-swarm in Morar and Moidart. However, magnetic anomalies are merely relative not discrete functions.

The marked extension of the area of negative anomalies south-westwards from Skye towards Canna may be of a certain significance. The lavas of Canna may be genetically related to those of Skye, and completely unrelated to the centre of igneous activity of Rhum. Such lavas of Canna are thought to be of late-stage (Ch.11:VIII), since they "bury" the postulated north-westerly extensions of the Rhum dykes. If these tenuous facts are true, then the indications are that some extrusions of lavas associated with volcanicity in Skye were later than the intrusion of the Rhum-Swarm of dykes.

Some comparisons can be made between the magnetic anomalies in the Area of Study and in the Hawaiian region. Malahoff and Woollard (1968) compared the computed magnetic effect due to the bathymetric and topographic features with the observed residual total force magnetic profiles across the Hawaiian ridge. They found that the observed anomaly is always much higher than the computed value. The strong bipolar magnetic anomalies observed are thus caused in part by the magnetization of prominent topographic features of volcanic origin, but mostly by underlying intrusive rocks extending down into the crust.

The trends of the residual magnetic anomalies over the Hawaiian ridge are parallel to major tectonic lines. The highest intensity anomalies are those associated with the crest of the Hawaiian ridge and major fracture zones, suggesting in places where the anomalies are elongate that they are caused by vertical dyke-filled rifts and volcanic plugs beneath volcanoes and ridges of volcanic rift origin (Malahoff & Woollard,1968,p.252). The conclusion is that such ridges of basaltic material and/or dyke-complexes may therefore underlie the axes of dilation in the Area of Study.

12:III. Gravity Anomalies.

High positive Bouguer anomalies in the Hebridean region (Browne & Cooper,1950,pp.299-300) were located during the submarine gravity surveys of 1938 and 1946. Browne and Cooper commented that the fact that the islands have undergone continuous submergence since the Ice Age indicates a return towards isostatic equilibrium. Why the original uplift occurred is problematic, although Browne and Cooper suggested that a possible explanation is that an upward convection current (now cooled or even reversed) existed beneath the region, and Tertiary igneous activity was probably closely associated with this rising current.

McQuillin and Tuson (1963) established 60 gravity stations on Rhum, Eigg, Canna, and Sanday. The contour-map of the Bouguer anomalies (fig.121) illustrates both the very localised nature of the anomaly and its rapid decrease away from the Rhum plutonic complex. Those authors attributed the cause of the anomaly to a density contrast between an extension at depth of the ultrabasic complex and the lighter sedimentary and granitic layers of the crust. McQuillin and Tuson calculated that the space-form of this gravitating ultrabasic (or possibly heterogeneous ultrabasic and basic) mass is either a vertical cylinder with a surface diameter of 6 miles extending downwards to at least 15km. (the thickness of the Intermediate Layer of seismology), or a truncated cone with a surface diameter of 5 miles, with sides inclined at 77 deg., extending downwards to at least the same depth. According to the authors the latter model is more consistent with the known geology, in that the diameter of the truncated cone is similar to that of the exposed ring-fault.

McQuillin and Tuson stated that similar results have come of other surveys (also, Tuson,1958), and the Bouguer anomalies over Tertiary Central Complexes are:-

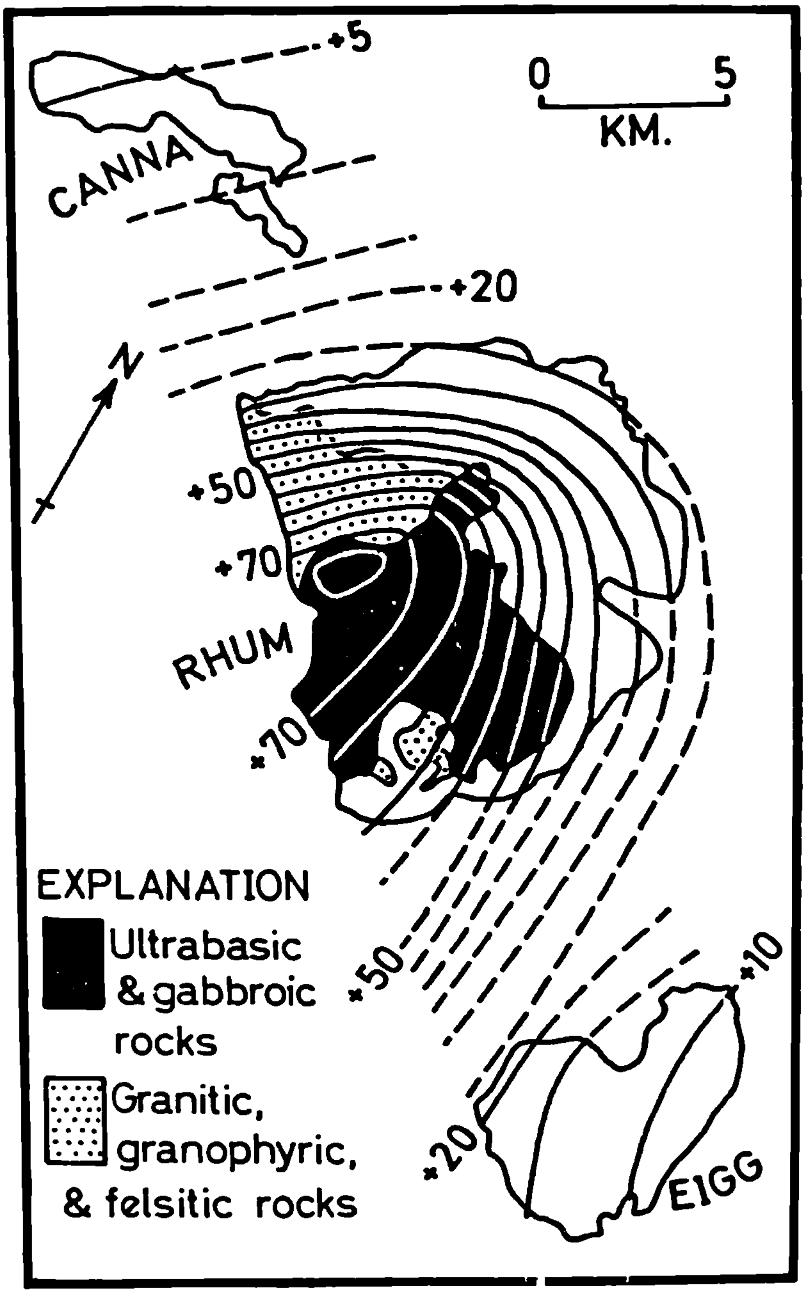


Fig. 121. "Bouguer anomaly map of the Islands of Rhum, Eigg, Canna, and Sanday in the Inner Hebrides. Contour interval, 5 milligals." Based on the work of McQuillin and Tuson (1963).

		Maximum Bouguer anomaly (mgal.)	Bouguer anomaly above background (mgal.)	Maximum gradient (mgal./mile)
McQuillin & Tuson (1965)	Rhum	76·3	65-70	16
	Skye	73·4	50-55	13
	Mull	71·7	50-55	9
	Ardnamurchan	42·0	20-25	8
	Arran	40·8	18-23	5
Cook & Murphy (1952)	Carlingford-Mourne	58·8 60·8		

McQuillin and Tuson (1965) also gave their interpretation of the contours of the gravity anomaly over the granite areas of the Tertiary Central Complexes of Rhum, Skye, Mull, Ardnamurchan, and Arran. They stated that over these areas "there are residual gravity 'lows', but these effects are relatively small and confirm the view that the Tertiary granites are thin for large surface areas" (McQuillin & Tuson,1965,p.60). The results of their analyses indicate that the granite bodies extend below sea-level no more than 600m. in Rhum, 600 to 900m. in Skye, and to a similar depth in Mull (Glencannel Granophyre). In Ardnamurchan outcrops of acid rocks are of minor importance, and the Bouguer anomaly map indicates no hidden development of such rocks. The granite body of Arran is thought to be no thicker than those in Rhum, Skye and Mull.

McQuillin and Tuson emphasized that their results do not constitute evidence of the origin of the granite bodies, since their association with the large basic masses provides either a source of acid differentiates or enough heat to fuse pre-existing metasedimentary and granitic layers.

12:IV. Palaeomagnetic Evidence.

Khan (1960) suggested that certain basic igneous rocks of the Central Complexes of Skye, Ardnamurchan, and Rhum were formed within the same one-half million years. This suggestion was based on palaeomagnetic data, and Khan's findings were that all these rocks, none of which showed self-reversing properties, are reversely magnetized and indicate approximately the same pole-positions.

12:V. Radiometric-Dates.

Radiometric-dating techniques give specific indications of the absolute age of the igneous rocks of the Tertiary province, although the dates (below) exhibit a spread far greater than the one-half million years proposed by Khan. Yet these dates correspond roughly to the same, Lower Eocene, age.

LOCALITY	SOURCE-ROCK	AGE m yr.	Mean m.yr	REFERENCE
SKYE	Southern Porphyritic Epigranite, W. Redhills	48±6	54±3	Moorbath & Bell, 1965
	Beinn an Dubhaich Granite, E Redhills	55±4		
	Gneiss xenolith in ferrodiorite, Harker's Gully	52±5		
	Porphyritic Felsite, W Redhills	51±4		
	Quartz diorite dyke, W. Redhills	54±2		
ARDNAMURCHAN	Quartz-monzonite of Centre 3	55±6		Brown & Miller, 1963
	Basalt dyke	26±4		Miller & Brown, 1965
ARRAN	Northern Outer Granite	65±6 to 55±5	ca. 60	Miller & Harland, 1963
	Central Complex Granite	63±6 to 60±6		
	Quartz-porphyry composite sills	61±6		

LOCALITY	SOURCE - ROCK	AGE m yr	Mean m yr	REFERENCE
MULL	Basalt Lavas	67±14		Miller & Brown, 1965
		33±6		
		61±12		
		60±12		
		81±16		
		68±14		
		70±14		
		52±10		
	Dolerite Plug	64±3		
LOCH FYNE	Phonolite Plug near the locality	59±3		Miller & Harland, 1963
AYRSHIRE & BUTE	Dyke at: Skelmorlie, Ayrshire (N.E. trend)	44±3		Grasty in: Smith, 1966
	" "	51±4		
	Largs "	53±2		
	Great Cumbrae Island, Bute	51±6		
	" " " "	41±3		
	" " " "	42±4		
	" " " "	34±1		
	" " " "	57±1		
LUNDY	G.1. Granite	50±3		Miller & Fitch, 1962
		55±3		
		52±2	52±2	Dodson & Long, 1962
		54±2		
		53±3		
		51±2		
	(Whole rock maximum age)	66±3		
MOURNE	G 1 Granite		75±7	Miller & Brown, 1963
ANTRIM	Basalt Lavas		74	Brown & Miller, 1963
ST. KILDA (& Boreray)	Acid dyke (felsite) (Boreray)	32±7		Miller & Mohr, 1965
	Granophyre of Conachair	56±1		
		57±3		
	Granophyre of Glen Bay	57±3		
		60±3		
		56±6		
	Granophyre sheet, An Torc	56±6		
	Olivine basalt, Mullagh Sgar	57±2		
	Olivine dolerite	62±2		
	Type '2' dyke (granophyre), Glen Bay	64±4		
	" " " (dolerite) " "	39±28		
ROCKALL	Aegirine granite (Rockallite): (weathered)	49±3		
	(fresh)	60±10		

12:VI. Concluding Remarks.

The locally steep gradients of the magnetic anomalies near the Central Intrusive Complexes of Skye, Rhum and Ardnamurchan are paralleled by similar gradients in the gravity anomalies. There is, however, a notable lack of either magnetic or gravity evidence for a latent centre off the south coast of Muck, although the contours of the magnetic anomalies extend southwards from Rhum towards Muck. One notable implication of the work of McQuillin and Tuson is that cylinders of basic magma extend beneath every one of the Tertiary Hebridean and the Carlingford-Mourne Central Complexes to a depth of at least 15km. Such enormous basic bodies (ca. 1000km^3 in volume) may have provided at least the source of material for dykes intruded in the near vicinity of such plutonic complexes. There is, however, little evidence from either gravity or magnetic surveys to suggest what form the dyke-swarms have in depth.

Evidence of the contemporaneous nature of the dyke-swarms of the Hebrides is found in their merging "connexions". Radiometric-dates, and palaeomagnetic evidence (Blundell,1957), suggest that the dykes of Lundy and the Lee Bay dyke of North Devon are of similar age to Hebridean swarms. The fact that the radiometric-dates on rocks of the Tertiary Central Complexes yield a spread of ages of over 10 million years may imply that the Hebridean, Irish, and Lundy dykes were intruded over at least this same period. The best confirmatory evidence of a geological type, which indicates a prolonged dyke-phase, comes from Mull where the youngest Tertiary rocks, e.g. the Loch Bà felsite, are injected by fewer dykes than are adjacent older rocks (Bailey et al.,1924).

Chapter Thirteen

A SUMMARY OF THE FORM AND STRUCTURE OF THE DYKE-SWARMS

(With some additional information)

13:I. Introduction.

The purpose of this chapter is as much to collate as to summarise the findings. Under several heads attempts are made to correlate the various properties of the swarms described in preceding chapters. Perhaps the most striking character of the swarms is found in the geographical distribution of the intensities of their dykes. The form of the axes of dilation is a particularly prominent feature. Affinities between the geographical behaviour of other functions and both the positions of these axes and the locations of the Central Intrusive Complexes, are the simplest (and perhaps from a structural point of view the most fundamental) of all relationships.

13:II. The Problem of the Time-Factor in Interpreting the Results of the Analyses.

Before summarising and correlating the properties of the dyke-swarms it is appropriate to review those problems relating to the factor of time. The obvious interpretation of the great variety of petrographical groups among the dykes (e.g. Harker,1904,pp.291-332; 1908,pp.152-81; Thomas in Richey et al.,1930,pp.350-6; Anderson & Dunham,1966,pp. 132-7) is that the dykes were intruded throughout the region over a long period of time. Conversely, monotony of composition is characteristic of swarms which are apparently of a single intrusive period, e.g. the swarms of the

Appalachians (de Boer,1967). The frequent occurrences of multiple and intersecting dykes in the Tertiary swarms of the Hebrides and northern Ireland constitute confirmatory evidence of their multi-phase intrusion, as do also the lower intensities of the dykes in younger plutonic bodies of the Central Complexes, and the wide range of ages (Ch. 12:V) of these same Central Complexes.

The relative ages of each of the linear-swarms and the subswarms are not, however, wholly indeterminate. Using the information at present available, it seems that the Broadford Bay-Applecross Subswarm may have been formed at a very early stage. The Scalpay Secondary-Swarm followed, predating the two N.E.-Subswarms. The main regional linear-swarm seems to have been largely restricted to the last stages.

It is difficult to assess the ages of the Small Isles and Ardnamurchan Swarms relative to that of the Skye-Swarm. The merging of the swarms one into the other indicates a roughly contemporaneous nature (Richey,1961,p.112), although the dykes of the Small Isles may predate those of the Skye-Swarm (evidence from the lavas of Canna, Ch.11:VIII). Observed cross-cutting relationships of dykes in the Small Isles are few. Three dykes of the Rhum-Subswarm are intersected by dykes of the main swarm. This scant evidence, and the obvious analogy with the Broadford Bay-Applecross Subswarm, indicate that the Rhum-Subswarm is earlier than the majority of dykes in the Small Isles.

13:III. Summary : General Correlations of the Properties of the Swarms.

For each of the swarms the trend-distributions of the dykes are of fairly Normal type. A pronounced peak at N.N.W. for the Skye-Swarm, and a similar but less pronounced peak for the Ardnamurchan-Swarm, are characteristic of the frequency-distributions. The trend of the dykes of the Small Isles has its maximum development in the range between N.W. and N.N.W., and the peak is of quite broad spread. Similar trend-distributions are found for other Tertiary swarms, e.g. Mull (Bailey et al.,1924), Arran (Tyrrell,1928), Lundy (Dollar,1941), and northern Ireland (Charlesworth,1963).

Most exceptions to the general N.N.W. to N.W. trend are concentrated in regions near the Central Complexes, where the subswarms are located. This phenomenon is frequently found in other swarms, e.g. Mull (Bailey et al.,1924), Arran (Tyrrell,1928), and the Wood's Point Dyke-Swarm in Victoria (Hills,1952).

On average, the dyke-trends veer in a manner paralleling the swing of the axes of dilation in the Skye regional linear-swarm. Such veering of dyke-trends is not developed in the Small Isles and Ardnamurchan where the dilation-axes are straight. The behaviour of the trends of the dykes of the Skye-Swarm is worthy of some emphasis, and fig.122 shows a series of trend frequency-distribution curves (expressed as percentages) for groups close to the main axes of dilation both to the north and to the south of the Central Intrusive Complex. The swing in trend is not developed to the north side of the Cuillins (groups '2' & '15'), but shows a gradual development with increasing distance from the Complex towards the south (up to group '00').

A swing of trend is found in the dykes of the Broadford Bay-Applecross Subswarm, and this again is accompanied by the corresponding curvature of the dilation-axis. If, as is probable, the Rhum-Subswarm extends to Soay, then a similar swing of the trends of the dykes and of the corresponding dilation-axis is again exhibited.

The trends of the axes of dilation in northern Skye lying to the east and west of the main axis, viz. those axes extending through Loch Harport on the one hand and Uig on the other, to some degree reflect the "fanning" of the trends of the dykes across the lava-pile terrains. Similar sub-radiate disposition of the trends of dykes is found for example in the Arran-Swarm (Tyrrell,1928), the Wood's Point Dyke-Swarm (Hills,1952), in the caldera wall of Hakone volcano (Kuno,1964), as well as in Rhum.

The variation in the trend of the dykes is of narrower spread at localities near the dilation-axes, except in the

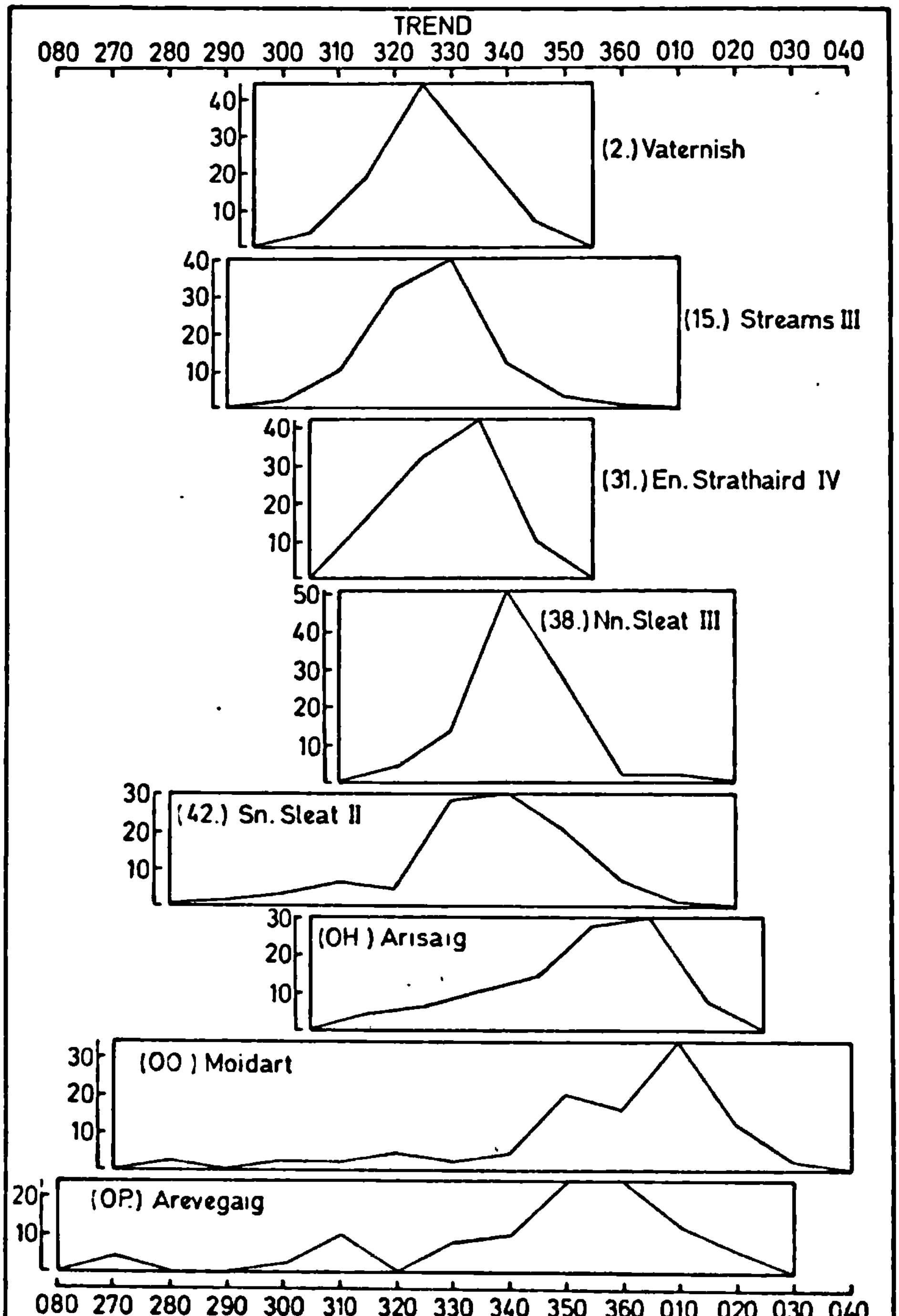


Fig.122. Trend of dykes in Groups close to main axis of dilation

Small Isles. The spread is generally narrower among dykes outcropping in the lavas; and this is also the case for the Small Isles dykes. The greatest spread for the Skye-Swarm is in regions to the north-east and south-west of the Central Complex, and also on the mainland. In this latter district the spread of trends can be partly attributed to the dual nature of the trends, in that some dykes cross-cut and others lie parallel to the strike of the Moine-foliation.

The standard-deviation and "normality" of trend-distributions are good indicators of the uniformity and degree of the spread. Standard-deviations are relatively lower nearer the dilation-axes (fig.123) and nearer the Central Complex of Skye, and "normal distributions" are more frequent and deviations generally lower in the lava-piles of Skye and the Small Isles.

The general increase in the density of the Skye, Ardnamurchan, and Small Isles Swarms towards their corresponding Central Intrusive Complexes is found for swarms in other parts of the Tertiary Province and throughout the world, e.g. Mull (Bailey et al.,1924), Mourne and Carlingford-Slieve Gullion (Tomkeieff & Marshall,1935; Charlesworth,1963), in Iceland (G.P.L. Walker,1959B;1964,p.355), in the Ben Nevis (J.G.C. Anderson,1935) and Loch Etive (Bailey & Maufe,1960) Swarms, and among the lower Carboniferous dykes of Scotland centring on the Misty Law and

Meikle Bin vents (Richey,1939). Certain exceptional behaviour of dyke-intensities in Tertiary swarms is found in Muck (the present author), Islay-Jura (Thomas in Richey et al.,1930,p.61; and later McCallien,1932,pp.51-5), north-west Donegal (Charlesworth,1963), the Ardglass-Killough district (Tomkeieff & Marshall,1940), and Co. Mayo (Emeleus & Preston,1969,p.62). In each of these exceptional cases dyke-intensities increase away from the nearest exposed Central Complex. Such behaviour is explained by the respective authors (in parentheses) as the result of the possible existence of latent centres at depth or concealed by the sea. In one case confirmatory evidence of such an unexposed intrusive complex has come from aeromagnetic and gravity surveys, viz. to the north-west of Islay (Roberts,1970,p.89).

It is evident that the Skye-Swarm is the most densely concentrated of all the Tertiary swarms in Britain and Ireland. Sloan (1970) found that the maximum value of dilation on the south coast of Mull is 10 per cent. The Arran Dyke-Swarm is very dense in parts, especially on the south coast of the island, but its intensity falls away rapidly, at least in the north-westward direction. The calculated minimal crustal-stretch along southern and eastern coasts of Arran, over 24km. in an E.N.E. to W.S.W. direction, is about 1½km. (Tyrrell,1928). The maximum crustal-stretch in Antrim is about 6 per cent. (G.P.L. Walker,1959A). Measurements of the total dilation across the whole breadths of other Tertiary swarms have yielded values such as: (i.) 0.3 per cent. over the 48km. breadth of the Islay-Jura Swarm (F. Walker, 1961,p.134); (ii.) $\frac{3}{4}$ per cent. in 32km. in the Ardglass-Killough district, Co. Down (Tomkeieff & Marshall,1940); and (iii.) 2.5 per cent. in 13km. in the Mourne-Swarm (Tomkeieff & Marshall,1935). In Iceland, G.P.L. Walker has obtained maximum values of between 10 and 20 per cent. dilation in the vicinities of volcanic centres (1959B;1964,p. 355).

In the Area of Study there is an almost exact coincidence of the axes of dilation and the axes of intensity by number of dykes (fig.123). This applies not only to the Skye and Ardnamurchan Swarms, but is also found in the Small Isles, though less well in the north-east of Rhum. A close correspondence between the axes of intensity of multiple-dykes and the dilation-axes is observed for the Skye-Swarm, including the Scalpay Secondary-Swarm (fig.123); and more especially is this evident to the south of the Central Complex. In Rhum and Ardnamurchan, however, a similar correspondence is not at all obvious, although a notable high intensity of multiple-dykes is observed near the postulated centre off the coast of Muck.

In general, the average thickness of the dykes in the Area of Study increases towards the axes of dilation (fig.

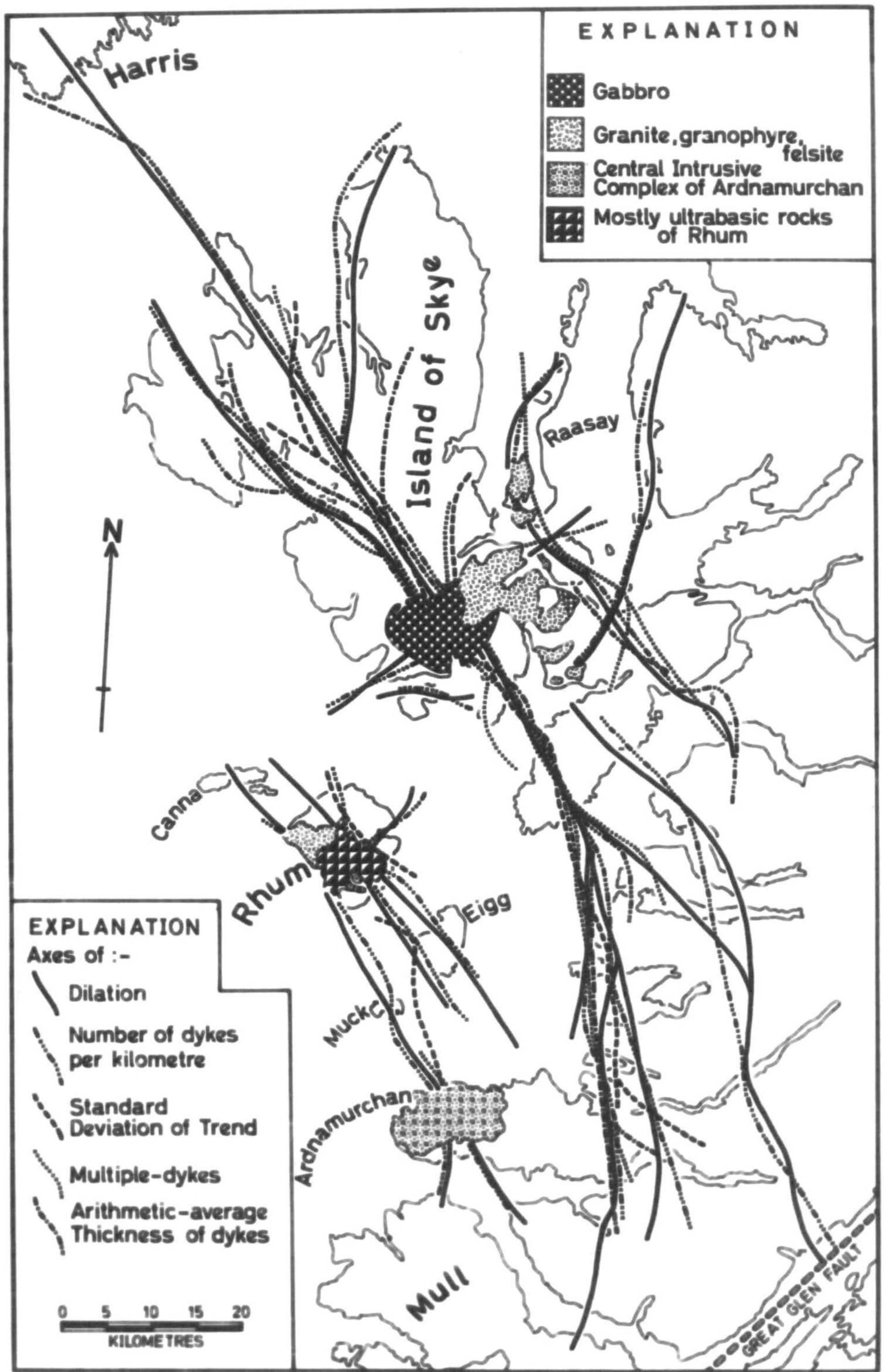


Fig. 123. Sketch-map to show the coincidence of the axes of distribution of some properties of the dyke-swarms of Skye, Ardnamurchan, and the Small Isles.

123) and decreases towards the Central Intrusive Complexes. The greatest spread of thicknesses is accordingly found in districts far away from the sites of these complexes. "Normal" distributions of thicknesses are characteristic of axial regions, especially near the Central Complexes and in the lava-piles. This is most pronounced in the case of the Skye-Swarm, and not so obvious in Ardnamurchan and the Small Isles.

The range of thicknesses among the dykes in the swarms studied is of the same scale as in other Tertiary swarms in Britain and Ireland. The average thickness of the dykes of Mull is 1.5m. (Bailey et al.,1924), of Arran 3.5m. (Tyrrell, 1928), of northern Ireland 3m. (Charlesworth,1963), and of Lundy 1.2m. for doleritic types and 3m. for intermediate or acid types (Dollar,1941). As in Arran (Tyrrell,1928), the average thickness of the dykes of the Skye and Ardnamurchan Swarms reaches a maximum for dykes of north-westerly or northerly trends, although this is not so marked among the dykes of the Small Isles. In the Skye-Swarm, the greater thickness of the northerly trending dykes can be accounted for by their occurrence mostly in the mainland districts of Morar and Moidart where they are (i.) at a considerable distance from the Central Complex and broad as a result, and (ii.) part-controlled in their trend by the foliation of the country-rock and often oriented N. to S.

The fact that narrow dykes are in the great majority in Strathaird, whereas narrow and broad dykes are in equal proportions in Sleat, might be of some significance. In Sleat it is found, however, that the narrow dykes have the same trends as the broader dykes, and are not of some different trend corresponding to the more westerly orientations of the dykes of Strathaird (fig.78).

The thickness of the dykes in all the subswarms, including that of the Small Isles, is similar to the correspondingly located members of the linear-swarms.

At the axes of dilation in the lava-pile of northern Skye, there are approximately equal proportions of S.W., N.E., and vertically dipping dykes. This is especially true along the main Vaternish axis and Loch Harport axis. Near the dilation-axes in Ardnamurchan, on the other hand, S.W. dips are in a marked minority to N.E. dips, and, to the north of the Central Complex, also to vertical dykes. In Rhum, S.W. dips are in a slight majority over N.E. dips though not over vertical inclinations, but elsewhere in the Small Isles N.E. dips predominate over S.W. dips. In the Scalpay Secondary-Swarm S.W. dips are in a minority to N.E. and vertical inclinations. In pre-Tertiary terrains the inclination of the dykes is mostly towards N.E. or is vertical. Similar dominance of easterly over westerly dips is found in other Hebridean swarms, e.g. on Arran where most of the dykes are vertical or sub-vertical but a few dip towards E. or N.E. (Tyrrell,1928).

The lack of any great symmetry of distribution of the dips of the dykes, e.g. about the dilation-axes, in the whole of the Area of Study, is possibly partly related to a subtle and gradual change of structural control during the emplacement of the swarms.

The "fanning" of the trend and the less obvious "fanning" of the dip of the dykes in the lavas of northern Skye reflects the major basin-form of the pile. Parallelism of the main dilation-axes with the axes of the lava-trough holds for Mull and Skye, but is not a general rule. The Tardree Dyke-Swarm, for example, trends at right-angles to the south-westerly pitching axis of the shallow trough structure of the Antrim basaltic lava-pile (G.P.L.Walker,1959A). The N.E. dips of the dykes in Eigg and Muck show the same relationship to the structure of the lavas as in Skye. In general the relationship between the trend and dip of the dykes to the north of the Skye Central Complex can be stated thus briefly: S.W. dips predominate where the more westerly trends are found to the south-west of the Cuillins; N.E. dips are predominant where the trends are more northerly, due north of the Cuillins.

13:IV. Dimensions of the Swarms.

In most linear dyke-swarms studied throughout the world the area occupied by the swarm is elongate parallel to the strike of the dykes. A notable exception to this rule is found in the Teanaway Dyke-Swarm (Foster,1958), in which the dykes have an elongate distribution perpendicular to the dyke-trend, the swarm being 72km. "wide" and little more than 8km. "long". In the Tertiary Hebridean and northern Ireland Swarms, the estimated average lengths and widths of the various swarms are about 150 and 20 to 35km., respectively. The Skye-Swarm has a length of 160km. and maximum breadth of 40km. Some swarms are much larger than the average, e.g. the Mull-Swarm and Carlingford-Slieve Gullion Swarm, which both extend to 300 or more kilometres, reaching at their south-eastern extremities north-eastern England and Wales, respectively. [Evidence for the Tertiary ages of the dykes of N.E. England comes from Holmes and Harwood (1929,p.4), and some of the dykes of Anglesey, north Wales and Shropshire comes from the analogous characteristics of their petrography, mode of occurrence and trends with those of the Hebrides (Greenly,1919,pp.684-95; 1942,p.329; Matley,1913,with pers. comm. by J.S. Flett,p.526; 1928,p.486; Archer & Elliot,1965,p.151; Pocock & Wray,1925, p.64).]

The dimensions of the Skye-Swarm and others described above are not uncommon in other swarms in the world, e.g. the Loch Etive (Bailey & Maufe,1960; Richey,1939), Independence (Moore & Hopson,1961) and Madagascar (Boulanger,1957) Swarms, and dyke-swarms of the Appalachians (de Boer,1967). On the other hand, the lengths of the swarms located on crustal-flexures and in Shield areas can be very great, e.g. the

Lebombo (du Toit,1930), east Greenland (Wager & Deer,1938) and Canadian Shield (Fahrig & Wanless,1963) Dyke-Swarms. There appears to be no general relationship of the thickness of the dykes to the areal-extent of any of the world's dyke -swarms.

There is a general correspondence between the widths of those linear-swarms which converge on Central Intrusive Complexes and the diameters of those Complexes. For example such relationships are found in the Mull (Bailey et al., 1924).Ben Nevis (J.G.C. Anderson,1935) and Loch Etive (Bailey & Maufe,1960) Swarms. For the Skye-Swarm exposures are sufficiently good to allow a determination of the limits of the main linear-swarm (excluding the Scalpay Secondary-Swarm), and this is found to be slightly broader than the diameter of the Central Complex. It appears that the same relationship holds for the swarms of Ardnamurchan and the Small Isles although lack of exposures across the full breadths of these swarms necessitates some conjectural projection of the dilation-contours.

13:V. Relationship of the Swarms one to another.

The separation of the Skye-Swarm from the Ardnamurchan -Swarm is at least a distinct geographic boundary. The gradation in intensities between the Skye-Swarm and the Mull-Swarm, and between the Ardnamurchan, Muck (postulated) and Rhum Swarms suggests that these may be so closely related as to preclude any absolute distinction, at least not one of genetic character. In similar fashion, the Arran-Swarm merges into both the Islay-Jura Swarm and the southerly extension of the Mull-Swarm. A poor separation of the swarms in northern Ireland might in part be attributed to the fact that lack of good and continuous exposure may have falsified the picture. It seems more likely, however, that these Irish swarms, too, merge imperceptibly one into the other.

The intensities of the dykes of the Small Isles and Ardnamurchan are very much less than those of the Skye and Mull Swarms. The reduced intensities of the Small Isles and Ardnamurchan Swarms and the poor development of their subswarms might be due to some restriction either of structural type or connected with the factor of time. This restriction is discussed for Ardnamurchan in the next section of this chapter.

The subswarms often seem to constitute connexions between major regional linear-swarms. The Central Complexes of Skye and Rhum are "joined" via the Rhum-Subswarm. The Central Complexes of Mull and Skye are "joined" by the N. to S. and N.N.E. dykes of a subswarm which appears near the Mull Central Complex and which passes through Morvern. The Central Complexes of Arran and Mull are connected through Bute in a similar manner. The Central Complexes of Rhum, Muck (postulated), Ardnamurchan, and Mull are connected by swarms whose intensities merge. One noteworthy aspect of the "Muck-Swarm" is that there is little evidence of attendant subswarms near its focus. Ardnamurchan is similarly poor in the development of subswarms.

The dykes of the Broadford Bay-Applecross Subswarm are in all ways analogous to the dykes in the connexions between the swarms of Rhum and Skye and Mull and Skye. Carried to their ultimate conclusion, interpretations of the Broadford Bay-Applecross Subswarm may indicate the location of a Tertiary centre off the coast of Lewis. The N.W. dykes of Lewis may be accounted for in this manner, and there does appear to be some confirmation of this hypothetical centre from the orientation of the magnetic anomalies near Lewis (Aeromagnetic map, Sheet 12, I.G.S.). Dykes of North Uist, on the other hand, may be a mixture of extensions from the Rhum-Swarm and the Skye-Swarm.

13:VI. Ardnamurchan — A "Restricted" Dyke-Swarm.

Richey (1939,p.423) attributed the sparseness of dykes in Ardnamurchan to possible mapping difficulties, or to the effect of the narrow and discontinuous border of pre-Tertiary rocks to the north-west and south-east of the Central Intrusive Complex. However, it is considered here that such low densities are real and also that the lack of N.E.-subswarms indicates that some restrictions on the development of the Ardnamurchan-Swarm were enforced. It is marginally possible that the swarm was of late-age — a view confirmed by the radiometric-dates of the Tertiary rocks of the Hebrides and northern Ireland (Ch.12:IV) — and formed at a period during which the regional forces controlling the swarms were waning. Alternatively, the Skye-Swarm possessed a structure in depth which could not be penetrated by many of the dykes of the Ardnamurchan-Swarm. The fact that the Central Complexes of Rhum and Mull are very nearby to that of Ardnamurchan seems to be of some significance. It could be that the Tertiary swarms were developed contemporaneously and that in some way the Ardnamurchan-Swarm was structurally repressed by the development of the Skye, Mull and, to a lesser extent, Rhum, Swarms.

13:VII. Closing Remarks.

Despite the various problems of interpretation of the form and structure of the swarms described in this thesis, striking correlations between the many properties of the dykes have been deduced by analysis. There remains to be discussed the significance of the findings of other workers relating to the great variety of petrological types among the dykes (Ch.14). Recognition and interpretation of local and regional controls on the structure of the dyke-swarms (Ch.15) culminates in Chapter Sixteen in the application of all the assembled results in formulating a mechanism of origin of the swarms.

Chapter Fourteen

SOME ASPECTS OF THE PETROLOGY OF THE DYKES AND THEIR FIELD-CHARACTERS

14:I. Introduction.

Of the 800 specimens of dyke-material collected from the Skye and Ardnamurchan Swarms and from the Small Isles, about 300 have been sliced and made up into microscope-slides. The specimens (usually taken from the middle part of the body) are of dykes selected in a manner such as to best ensure random sampling of the swarms. Wherever it was possible specimens were taken of every tenth dyke observed.

At the time of writing, the petrographic analyses are still in their early stages, and it is not proposed to discuss them until all the collected specimens have been sliced. Upon the acquisition of all such thin slices, the author's intention is to analyse the petrographic types, with a view to the discovery of any patterns of geographical distribution not hitherto described. Such patterns may indicate courses to be followed in later more detailed studies.

In this thesis the most constructive course then is to review the field-characters of the dykes, and to summarize what is already known of the petrology of the dykes, especially aspects pertinent to this present study. Dykes omitted from discussion here (Ch.5:IV) are chiefly the acid and composite types.

14:II. Field-Characters of the Dykes of the Regional Linear -Swarms and Subswarms in the Area of Study.

Many of the phenomena described in sub-sections a. to h., below, are the observations made by Harker and Clough (Harker,1904,pp.291-332) in Skye. The observations are fully corroborated by the present author, and the features described are shown by dykes throughout the whole of the Area of Study.

(a.) Weathering of Dykes. The dykes are mostly fresh, although some of the more basic types weather deeply and have crumbly surfaces. Differences of composition or jointing within a group of dykes emplaced in the same country-rock produce differential weathering, with some dykes standing as ridges and others eroded as troughs, e.g. in eastern Strathaird.

(b.) Dyke-Margins. Decrease of grain-size, lack of phenocrysts, and usually lack of amygdales are generally observed at dyke-margins.

(c.) Composition of Dykes. The thinner dykes are usually of uniformly fine grain-size, except where they are narrow off-shoots of broader feldsparphyric dykes. Apart from marginal modifications the mineralogical composition of a dyke is uniform throughout. Some of the ultrabasic dykes of the Cuillins are exceptional (Wager et al.,1948). Gibb (1968) concluded that, in the ultrabasic dykes of the Cuillins and Strathaird, concentration of olivine phenocrysts into central bands in the dykes occurred during laminar flow differentiation of the suspended olivine crystals during dyke-intrusion.

(d.) Amygdaloidal Varieties. In amygdaloidal dykes which are generally of finer-textured varieties, the amygdales are often concentrated in central bands within the dyke.

(e.) Flow Phenomena. Evidence of the flow of magma in a dyke is of three chief types: (i.) orientation of feldspar phenocrysts with their long axes parallel to the margins of the dyke, (ii.) elongation of amygdales, and (iii.) alternations of bands parallel to dyke-margins of varying sizes of amygdales or feldspar phenocrysts. The subject of flow in dykes is expanded later (Ch.15:II).

(f.) Xenoliths. Dykes containing xenoliths are of widespread occurrence. Harker (1904,pp.351-63) distinguished two types of xenolith: (i.) accidental xenoliths, e.g. of quartz and quartzite, and (ii.) cognate xenoliths of granite and gabbro more common in dykes near the Central Complexes. Sometimes granitic xenoliths are partially dissolved, resulting in modifications of the composition of the basic dyke, whereas gabbroic xenoliths are often very little altered.

To explain (i.) the occurrence of xenoliths of gabbro and granite in dykes located at considerable distances from the Central Complex of Skye, e.g. in southern Sleat, and (ii.) the abundance of xenoliths in some parts of a dyke and their scarcity or absence in other parts at short distances along the dyke's length, Harker (1904) proposed that an earlier dyke may have been locally destroyed, except for fragmentary relics, by the intrusion of a later dyke of different composition. As an alternative, Harker suggested that the later dykes may have broken up a magma reservoir, portions of which consolidated slowly at depth, and in this case the xenoliths could be co-extensive with the geographical distribution of the dykes. To apply this argument to both types of xenoliths Harker was forced to envisage the co-existence of acid and basic magmas.

(g.) Joints. In most dykes contraction during cooling has produced shrinkage joints, commonly columnar perpendicular to the dyke-walls. The separation of adjacent joints in large dykes is greater towards their middle portions (Plate 1). Harker (1904) thought that the formation of platy joints parallel to the dyke-margins, especially common in the dykes of south-eastern Skye, is possibly associated with the flow of the magma. The correlation of such platy joints with other flow phenomena seems to verify Harker's opinion.

(h.) Metamorphism. Metamorphism of the country-rock by a dyke could be indicative of long-continued flow of magma through the fissure. For example, R.L. Wilson (1964,pp.254-7) thought that certain Tertiary dykes in Ireland which had caused extensive metamorphism were probably feeders to lava-flows. Metamorphism of the country-rock in the Area of Study is, however, rarely seen, except where the dykes are densely crowded. Metamorphic effects produced by the dykes are mainly of the following types: (i.) development of platy-jointing and, more rarely, production of calc-silicates in Liassic shales, e.g. near Camasunary (Harker in: Peach et al.,1910,p.146); (ii.) induration of sand-stones, e.g. in Strathaird; (iii.) partial de-oxidation of red sandstones, e.g. Torridonian arkoses and grits; (iv.) hardening and alteration from green to dark-grey of Lew-isian schists; and (v.) possible induration of the Durness Limestone, although as Harker (1904,p.311) said the alter-ation effected by the Beinn an Dubhaich granite intrusion somewhat confounds a determination of the validity of this.

14:III. <u>Historical Review of the Petrographic Classifica-tion of the Tertiary Dykes in the Area of Study</u>.

At present the petrographic classification of the dykes in the Area of Study in particular, and in Hebridean swarms in general, is unsatisfactory. Many different and sometimes overlapping classifications have been used.

Harker (1904) based his rather muddled classification of the dykes of Skye on more than their petrography alone. Where possible he compounded dyke-sets, i.e. groups of characteristic petrography and age and often of restricted geographic distribution. Because of the rarity of intersections of dykes in the Small Isles, due to their general parallelism in individual localities, Harker's (1908) classification of the dykes of the Small Isles was much less complex and more strictly petrographic than that for the Skye dykes. Thomas (Richey et al.,1930,pp.350-6), in his description of the petrography of the dykes of Ardnamurchan, followed the format used by Bailey and Thomas (1924,pp.368-76) in their description of the dykes of Mull. Bailey and Thomas had divided the dykes of Mull into several petrographic groups some corresponding in texture and composition to the Tertiary lavas of Mull. On the lines of a modern petrographic study, Anderson and Dunham (1966,pp. 149-58) presented details of the dykes of northern Skye.

14:IV. Advantages of Petrographic Studies.

Some indications of the advantages of detailed analyses of the petrography of the dykes in the Area of Study are found among the works of earlier researchers.

A separation of swarms might be facilitated by petrographic studies. In Arran, for example, Tyrrell (1928, pp.238-54) discovered that crinanites and tholeiites outcrop near the Central Complex, but only tholeiites are found away from it. Tyrrell suggested that the tholeiites of Bute and Arran might be satellites of the Mull-Swarm. Later McCallien (1932,pp.51-5) divided Tyrrell's "Arran-Swarm" (encompassing the dykes of Islay, Jura, Kintyre, and Arran) into: (i.) the Islay-Jura Swarm, focussing to the north-west of Islay (near Dubh Artach), and composed largely of olivine-dolerite dykes, and (ii.) the Arran-Swarm, focussing on three regions (the Northern Granite of Arran, the Central Complex of Arran, and Ailsa Craig), and composed mainly of crinanites and tholeiites. This division was based not only on the petrographic differences between the dykes of the two swarms but also on the low intensity of dykes in Kintyre (fig.2, for location).

It is conceivable, though perhaps only remotely so, that the thicknesses of the dykes might bear some relation to petrographic types. Holmes and Harwood (1929,p.42), for instance, noted that the thicker tholeiite dykes of northern England are of only two types (Acklington and Cleveland types), whereas the thinner dykes are not only of these same two types but also of three others (Salen, Brunton, Talaidh types).

A study of the petrology of the dykes might yield evidence on the nature of the parent magma of the igneous cycle in the Area of Study. Holmes (1929,pp.49-50) for the tholeiites of northern England, Tomkeieff and Marshall (1935) for the dykes of Mourne, and Rao (1959) for the dykes of Arran, each proposed that mixing of two magmas, basic and acid, might explain the varieties of petrographic types. F. Walker (1961), on the other hand, believed that a continuous differentiation series was operative during dyke-emplacement in Arran. Anderson and Dunham (1966,pp. 160-70) believed, from the evidence afforded by both lavas and dykes, that tholeiitic magma was available at the commencement of volcanic activity in northern Skye and again when the latest dykes were intruded, but that the majority of extrusions and intrusions are of alkaline basalt and its differentiates (picrite, allivalite, and the mugearite-trachyte series). Anderson and Dunham (1966,p.170), however, did not make an inference as to the constitution of the ultimate primary magma.

In many ways the dykes could give a clearer indication than the lavas of the variety of magma-types which were available throughout the whole igneous cycle (cf. Bailey et al.,1924; Kennedy,1931). Harker (1904,p.315) and Anderson and Dunham (1966,pp.138-9) believed that certain petrographic types among the dykes of Skye (especially the non-porphyritic olivine-dolerites) were repeatedly intruded throughout the whole igneous cycle (Ch.2:II). If this is true, then unless the different types can be dated relative to each other, a magmatic-sequence will be determined only with great difficulty.

The restriction of acid dykes to, and the more frequent occurrence of ultrabasic and intermediate types in, the neighbourhood of the Tertiary Central Intrusive Complexes throughout the Hebrides and northern Ireland, constitute significant evidence of the availability of different magma types in these localities at least.

14:V. The Geographical Distribution of Petrologic Groups.

On the basis of their field-relationships the dykes of northern Skye were separated by Anderson and Dunham (1966,pp.132-9) into three groups: (i.) trachytic, mugearitic, picritic, gabbroic, and doleritic (including a proportion of the olivine-dolerites and feldsparphyric dolerites) dykes, each associated with corresponding lava-groups; (ii.) the big gabbro dykes of the central area; and (iii.) the dolerite dykes which Anderson and Dunham described as "regional" and which include both non-porphyritic and feldsparphyric types of olivine-dolerite, as well as tholeiitic types.

Anderson and Dunham's conception of "regional" dykes included only those which were intruded after the extrusion of all the Tertiary lavas, i.e. during the final collapse of the lava-field. The present author's view of the term regional is not entirely consistent with Anderson and Dunham's concept. On the basis of the regularity of the distribution of the dykes (Ch. 7 & 8) the present author has been obliged to include all dyke-sets of roughly N.W. trend under the head of regional dykes, and in this respect the author agrees with Billings' (1954) opinions (Ch.4:VI).

A useful summary of the detailed petrography of each of the various types in the three groups of dykes in northern Skye was presented by Anderson and Dunham (1966,pp. 149-58), and will not be duplicated here. In the context of this thesis the most important aspect of Anderson and Dunham's findings is the distribution of the various types of dykes in dyke-sets and those of "regional" type. Added to this, the writings of workers (Harker,1904; 1908,pp.152-161, 168-9, 176-81; Davidson,1935; Thomas in: Richey et al.,1930,pp.350-6) covering other parts of the Area of Study indicate that similar geographical groupings into dyke-sets are possible.

Trachytes and Mugearites. In northern Skye the trachyte and mugearite dykes probably constitute a close petrogenetic association, as do the corresponding lava-types.

Non-porphyritic trachyte dykes occur in a group near the head of Loch Harport (Drynoch group of Harker,1904). This group occurs entirely within an area occupied by the trachyte lavas and the dykes are probably genetically related to the Cuillin Centre (Anderson and Dunham,1966,p. 133).

The Broadford, Loch Eishort and Sleat trachytes — also recognized by Harker (1904) — constitute a distinct group, possibly of later emplacement than the Drynoch group (Anderson and Dunham,1966,p.133). Trachyte dykes in the

Glenelg district belong to the same group. The number of trachytes in the group is markedly subordinate to the feldsparphyric dolerites and olivine-dolerites in the same areas.

The mugearite dykes of northern Skye, like the corresponding lavas with which the distribution of the dykes is closely associated, are in some cases non-porphyritic in others feldsparphyric. The mugearite dykes are not a common group in northern Skye: a mere twenty have been mapped (Anderson and Dunham,1966,p.133).

Throughout the remainder of the Area of Study the numbers of "intermediate" dykes are low: a very few are found in Raasay (Davidson,1935), Ardnamurchan (Thomas in: Richey et al.,1930), and the Small Isles where most especially in Muck mugearites occur (Harker,1908).

Picritic Dolerites. A few dolerites of picritic affinity (rich in olivine and augite) and associated gabbroic dolerites are among the latest of the minor intrusions in northern Skye (Anderson & Dunham,1966,p.135).

Gabbroic Dolerites, Allivalites and Peridotites. In northern Skye a group of big gabbro dykes are closely related petrographically and geographically to a contemporaneous group of allivalite dykes. The dykes occur in an area lying near the major dilation-axis to the north-east of Bracadale, and they intersect the most recent lava-series. Petrographic evidence (Anderson & Dunham,1966,p.170) indicates that these coarse-grained dykes were intruded as a crystal-mush lubricated by a small proportion of alkali basalt magma. Other big non-porphyritic gabbroic dolerites are sparsely though widely distributed elsewhere in Skye, and as such do not constitute a dyke-set.

Groups of peridotite dykes of extremely restricted occurrence include:. (i.) a radial group occurring only in the western Cuillins and Strathaird (Harker,1904), (ii.) a single N.E. to S.W., possibly radial, dyke in Raasay (Davidson, 1935), (iii.) a small group of peridotites in southern Rhum. The first of these groups is excluded from the regional linear-swarm of Skye (Ch.5:IV).

Normal Olivine-Dolerites and Feldsparphyric Dolerites. The olivine-dolerites include non-porphyritic varieties (formerly referred to as the Plateau Basalt type by Bailey and Thomas,1924,pp.367-76) and porphyritic types. Feldsparphyric dolerites were formerly designated the Porphyritic Central type by Bailey and Thomas.

The majority of dykes in northern Skye are non-porphyritic olivine-dolerites of various periods of intrusion (Ch.2), and are mostly widespread and of "regional" (Anderson and Dunham's terminology) type, though a minority are associated with corresponding lava-types (Anderson & Dunham, 1966,p.134). Among other localized dyke-sets recognized the most important are: (i.) a group of ophitic feldsparphyric olivine-dolerites in the Camasunary and northern Sleat districts (Harker,1904) and (ii.) a group of feldsparphyric olivine-dolerites with patches (3mm.) of more acid material located in Scalpay (Harker,1904).

Elsewhere in Skye and on the mainland both non-porphyritic olivine-dolerites/basalts and feldsparphyric olivine-dolerites (the latter sometimes porphyritic also in olivine and augite) are common, widespread, and thus "regional" (Harker,1904; Anderson & Dunham,1966).

In Raasay nine-tenths of all the dykes are alkaline olivine-basalts (Davidson,1935). In Ardnamurchan olivine-dolerites/basalts and feldsparphyric dolerites are common, though subordinate to tholeiites and quartz-dolerites (Thomas in: Richey et al.,1930). Both non-porphyritic and porphyritic olivine-dolerite/basalt dykes are widespread in the Small Isles (Harker,1908).

Crinanites and Teschenites. Feldspathoidal variants of normal olivine-dolerites, i.e. crinanitic and teschenitic dolerite dykes, share a common distribution in northern Skye (two groups in Trotternish and one near Dunvegan Head), and to some extent are both associated with corresponding lava-types (Anderson & Dunham,1966,p.135).

Tholeiites and Quartz-Dolerites. Anderson and Dunham (1966, p.157) found that about one-third of the doleritic or basaltic dykes of northern Skye can be described as tholeiites, a few of which are porphyritic in calcic plagioclase. Although these dyke-rocks have a paucity or absence of olivine and have intersertal glass or devitrification products, the tholeiites of northern Skye are not entirely normal in that they are not characterized by orthopyroxene or pigeonite. Moreover, undoubted components of an alkali-basalt body may be tholeiitic to the extent that they are poor in olivine and have intersertal glass. Anderson and Dunham (1966) added that not a single quartz-dolerite has been found in northern Skye.

The tholeiitic dykes of Skye, such as they are, are mostly of late-stage ("regional"), although tholeiitic magma was also available at the beginning of volcanic activity (Anderson & Dunham,1966,p.170). One tholeiite dyke has been found in Raasay (Davidson,1935).

Tholeiites and quartz-dolerites are found in Ardnamurchan and the Small Isles, and especially in the former where they constitute the majority of the dykes (Thomas in: Richey et al.,1930; Harker,1908).

14:VI. Concluding Remarks : Chemistry.

During the eruption in Skye of the first (tholeiitic) lavas and the later emplacement of feeder dyke-sets and allied lavas, the Cuillin centre cannot be shown to have been active (Anderson & Dunham,1966,pp.160-2): the lavas for instance do not increase in thickness towards the Cuillin Gabbro. An explanation of this may lie in the deep-seated nature of the cylindrical basic pluton, rising to higher levels only during the later stages of volcanicity (Ch.16: VIII). The chemical evidence in northern Skye (Anderson & Dunham,1966,p.164) indicates a transition, though not complete, within the alkali olivine basalt-mugearite-trachyte series of lavas and dykes. Anderson and Dunham (1966,pp. 165-70) suggested that (i.) gravitational or flow separation of an olivine-rich cumulus, (ii.) the stage of eruption of a lava in relation to the temperature change accompanying such eruption, and (iii.) the escape of gases, are the factors contributing most to the observed variation of petrologic types of lavas and dykes in northern Skye. The picritic and picrodoleritic sills (of Trotternish) and dykes illustrate that a concentration of early-separated olivine has occurred (Anderson & Dunham,1966,p.165).

Fractional crystallization and separation of solid phases from a Hebridean basalt of average composition yields complementary mugearite and eucrite or complementary trachyte and gabbro, the latter in each of the two cases characteristic of the plutonic bodies of the Cuillins. Processes of assimilation to produce the observed variation of most of the volcanic rock-types were considered unlikely by Anderson and Dunham, since large bodies of the appropriate composition (quartz-syenite) were not available. Allivalitic types are believed (Anderson & Dunham,1966,p.170) to have been derived as in Rhum (Brown,1956) by mobilization of portions of a bytownite-anorthite cumulus. Crinanitic and teschenitic types illustrate the action of volatiles during crystallization, while amygdaloidal varieties resulted from late-stage action of volatiles (Anderson & Dunham,1966,p. 169).

Chapter Fifteen

LOCAL AND REGIONAL CONTROLS ON THE STRUCTURE OF THE DYKE-SWARMS. THE BROADER STRUCTURAL SETTING OF THE DYKE-SWARMS

15:I. Introduction.

Prior to postulating hypotheses on the mechanism of origin of the dyke-swarms in the Area of Study, a review is given in this chapter of what are essentially observable controls which have influenced the form and structure of the dyke-swarms. To interpret such controls as the influence wielded by (a.) the earlier on the later members of multiple-dykes, (b.) pre-existing foliations and joints in the country-rocks, and larger penecontemporaneous fold structures in the lava-pile terrains, and (c.) pre-existing faults and fractures in the country-rock, it is necessary first of all to establish what is to be accepted as the mechanism of intrusion of individual dykes.

As a prologue to Chapter Sixteen, the broader setting of the dyke-swarms of Skye, Ardnamurchan and Rhum within the North Atlantic Tertiary Province is briefly discussed in the latter part of this chapter.

15:II. Mechanisms of Intrusion of Individual Dykes.

(i.) Active or Passive Dilational Mechanisms. Undoubtedly most, if not all, of the dykes of the Tertiary Hebridean swarms were emplaced by a mechanism of dilation. Corroboration of this mode of emplacement for the Mull-Swarm, for example, comes from mid-Argyll. Here independent lines of evidence, viz. changes in the trends of an Old Red Sandstone dyke-swarm and N.N.E. tear-faults as well as variations in the strike of the Dalradian country-rocks, indicate a crustal-distortion equivalent to the extension produced by the injection of the Tertiary dykes (Knill,1960). The question, to which certain allusion was made earlier (Ch.4:II & 7:I), of the passiveness or activeness of the intrusion of the dykes, however, remains unanswered.

Favouring a passive mode of emplacement, van Bemmelen (1937,pp.481-4) believed that the intrusion of dykes is a result of "negative" hydrostatic pressure in potential vacua. He said that an arching up of the crust above an expanding differentiating magma in the Intermediate Layer (so-called "undations") produces tensional stresses perpendicular to the geanticlinal axis. These stresses are relieved by block -faulting and fissuring. Van Bemmelen postulated that a large-scale geo-undation, extending from the British Isles towards Greenland, is the prime cause of the emplacement of the Tertiary linear dyke-swarms, with their greater concentrations near the sites of Central Intrusive Complexes, where the ascent of and processes of stoping of the magma had weakened the crust.

E.M. Anderson (1951,pp.22-5), on the other hand, favoured an active mode of emplacement of the deeper-seated (below 8km.) varieties of dykes. He proposed that these dykes were fed from a deep and perhaps horizontal magmatic layer — probably lying at 30 to 40 km. depth for the Tertiary swarms of Britain — and that they propagated vertically upwards by a process of magmatic wedging. If the magma pressure in a dyke is even only slightly greater than the confining horizontal pressures in the country-rock, then, Anderson argued, a large horizontal tensional force will be developed across the end of the wedge-like termination of the dyke. This tension will cause extension of the fracture, and thus also of the dyke-injection, upwards, so long as the horizontal principal pressure in the rock is less than the hydrostatic pressure of the magma. Anderson's (1951,p.44) analysis of certain Tertiary N.W. faults in Britain led him to the conclusion that a N.E. to S.W. "system of relative tension must have extended over nearly the whole of Britain". Hills (1963,p.371), commenting on Anderson's hypothesis, added that the possible influence of shock-waves might have to be considered, especially in the initiation of cracks.

Some corroboration of his theory is cited by Anderson himself (1951,p.46) and concerns Lamplugh's (1903,p.327) remarks on the upward termination of certain N.W., possibly Tertiary dykes of the Isle of Man, at 700 feet A.S.L., some 1300 feet below the summit of the island. Lamplugh attributed this phenomenon to an insufficiency of the hydrostatic pressure of the magma to allow dykes to reach any higher levels than they did. In Argyll a similar restriction in the vertical range of Tertiary dykes was observed by J.B. Hill (1905,p.117). At the present-day in Iceland there are gaping dilation-fissures in which the magma failed to reach the surface (G.P.L. Walker,1965,p.27). Other evidence in favour of Anderson's ideas, that dykes are intruded parallel to the direction of the principal horizontal stress, has come from Foster (1958) and Challis (1961).

Ramsay and Sturt (1970) were of the opinion that both active ("intrusion fracturing") and passive (using actual or incipient fractures) mechanisms could operate in the same suite of dykes. The present author's own view is that the intrusion of the Tertiary Hebridean dykes can also only be described as partly passive and partly active. The wedging mechanism proposed by Anderson may well have been operative, but some pre-intrusion tectonic fissuring under the influence of if nothing else a regional tensional force, whether the fissures were gaping or not, was a necessary forerunner of the uprise of magma in sheet-like bodies which ultimately consolidated to form dykes.

(ii.) Lateral or Vertical Flow of Magma. Bailey (1960,pp. 200-2) implied that the N.E. dykes of the Etive and Ben Nevis Caledonian Swarms were emplaced laterally, emanating from central ring-dykes or ring-bosses. Such dykes were injected under conditions of a N.W. relative tension, and the dykes were located above an underlying magma reservoir, since this latter was incapable of sustaining tensional forces (Bailey,1960). This reservoir, however, was not itself believed by Bailey to be the source of the dyke-material. In Mull, too, Bailey (1924,pp.10 & 360) suggested that the frequent subterranean weakness of the magma of the Central Complex had served as a localizer and injector of the Tertiary dykes.

Some of the dykes of the Tertiary Hebridean swarms attain great horizontal extent, whilst maintaining a uniform thickness. This is not a feature of rare occurrence and is found throughout many of the world's dyke-swarms, e.g. in the Canadian Shield (Fahrig & Wanless,1963) and Appalachian (de Boer,1967) areas. Horizontal flow of magma over such long distances, especially in an intrusive body of narrow breadth which is in contact with what there is no reason to believe were anything but cold country-rocks, is inconceivable. Moreover, as E.M. Anderson (1951,p.43) remarked, because of the variety of rock-types among the dykes, lateral flow from a central magma chamber must incorporate the requirement that this chamber be filled with successively different types of magma. His alternative proposal of vertical flow from sheet-like reservoirs at different levels in the crust (a view not dissimilar to that of Holmes and Harwood,1929,p.43), with the central plutons acting only as regions of weakness from which fractures propagated (E.M. Anderson,1951,p.26), obviates this need.

Indications of the direction of flow of magma in a dyke-fissure are observed in the elongated amygdales of some dykes. Balk (1937,pp.45-54) described such elongations of amygdales parallel to the margins of dykes as internal flow structures of "conformable type". Balk's idea was that unequal rates of flow produced by friction at the walls of the dyke causes a part of the magma rich in gas bubbles to flatten in the plane of least resistance.

Although not as precise as Balk in his views on the origin of elongated amygdales, Clough (in Harker,1904,pp. 389-93) at an earlier date had given his opinion that such elongate amygdales in the dykes of the Skye-Swarm indicated that a component of horizontal flow was of great importance. By investigating the relationship between the orientations of elongate amygdales and of rods of spherulitic bodies (common in the trachytic and andesitic dykes of southern Skye and the adjacent mainland), Clough concluded that the alignment of the latter structures is also probably parallel to the direction of flow. Both these types of linear structure indicated in some dykes a horizontal, in other dykes a vertical, and in yet others a diagonal, direction of flow. In some cases a diagonal flow-direction would dip towards N.W. and in others towards S.E. Similar flow-phenomena were observed a few years later in the dykes of the

Small Isles (Harker,1908,p.150).

The results of Clough's observations in Skye and the adjacent mainland were that indications of vertical flow are rare, whereas indications of horizontal and diagonal flow are much more frequently seen. Clough (in Harker,1904, p.390) concluded that "the materials of some dykes have travelled for great distances in a direction not very far from horizontal from some source of comparatively limited extent near one end of the dyke outcrop".

Clough's hypothesis does help to explain why a dyke of uniform composition can be found in the midst of other dykes of equally uniform but very different compositions, since their source magmas may be considerable distances apart. Yet it is untenable as a complete solution, since horizontal flow over several kilometres through relatively cold country-rock is a physical impossibility. Geikie (1897B, Chapter XXXV) offered a partial solution of this latter problem by postulating that a magma rose passively at several points and flowed into a fissure immediately after this was rent in the crust. Such feeding of a fissure at several points along its length gave rise to somewhat lateral flow of limited extent, although the main component of the direction of flow was vertical.

15:III. Local and Regional Controls on the Structure of the Dyke-Swarms.

(a.) Introductory Remarks including Some Examples of the Observations of Other Workers outside the Area of Study.

The more obvious controls on the properties of the dykes within the Area of Study are: (i.) a regional control at the time of emplacement, (ii.) the influences of pre-existing or contemporaneous structures such as fractures, joints, faults, cleavage, bedding, and folds, and (iii.) regional deformation of local groups or the whole assemblage entirely after their emplacement. Younger dykes of multiple-intrusions may have been injected under an additional special circumstance, i.e. the later dyke may have been controlled locally in its orientation by the earlier dyke of the multiple body.

The character of the regional control operative during the emplacement of the swarms is broadly the subject of Chapter Sixteen, and of necessity includes an analysis of the deformation of all or parts of the dyke-swarms after their emplacement. The influences of the structures listed under (ii.), above, including the controls exerted by earlier on later dykes form the current topic of discussion.

Although little has been written in a quantitative manner about the control of earlier members of multiple-dykes, such control has sometimes been a topic of qualitative discussion by earlier workers. Where pre-existing or syntectonic structures of other types are concerned, however, numerous and varied are the references and statistical analyses made by other authors to the influence of these.

The parallelism of dykes to pre-existing or incipient joints, fractures or faults has been observed, for example, in Arran (Tyrrell,1928), north-west Donegal (Charlesworth, 1963), Lundy (Dollar,1941), the Cheviot Hills (Carruthers et al.,1932,pp.96-8), south-west Madagascar (Boulanger, 1957), the Wood's Point Dyke-Swarm (Hills,1952), the Beartooth Mountains Swarm (Spencer,1959; Prinz,1965), the Spanish Peaks Swarm (R.B. Johnson,1961), the Lyttelton Dyke-Swarm (Speight,1938), and in a Caledonian swarm of north-west Norway (Ramsay & Sturt,1970).

Parallelism with cleavage and/or bedding-planes in the country-rock has been observed, for example, again in Arran (Tyrrell,1928), in the Wood's Point Dyke-Swarm (Hills,1952), in the linear-swarm of south-west Madagascar (Boulanger, 1957), as well as in the Ben Nevis (J.G.C. Anderson,1935) and Ards Peninsula (Reynolds,1931) Swarms.

Parallelism in some cases and perpendicularity in others to pre-existing or syntectonic fold-axes in general has been observed in such swarms as those of Iceland (G.P.L.

Walker,1959B; 1964,p.357; Rutten,1964) and Greenland (Wager & Deer,1938), in the Spanish Peaks Swarms (R.B. Johnson, 1961), the north-eastern South Island (N.Z.) Swarm (Challis, 1961), the Lebombo Swarm (du Toit,1930), the Appalachian Swarms (de Boer,1967), the Teanaway Swarm (Foster,1958), the Independence Swarm (Moore & Hopson, 1961), and in some of the clusters and swarms of dykes of a post-lava hypabyssal phase of the Deccan (Auden,1949).

(b.) The Influence of the Earlier on the Later Members of Multiple-Intrusions. If many or all of the later dykes of multiple-intrusions within the Area of Study were emplaced during a late episode, then they may have been subject to somewhat different regional controls than the earlier dykes. The table below details an attempt to analyse the form, if any, of special local controls on the dips of later members of multiple-dykes. Throughout the four regions of this table, the dominance of N.E.-dipping dykes is apparent in the total numbers of fissures, and also in later members of multiple-intrusions. South and east of the Central Complex of Skye the proportions of N.E.-dipping younger dykes is markedly greater than among the total number of fissures in the same region. It appears, therefore, that a later regional control brought about this increase. To the north of the Central Complex of Skye, N.E. and vertical inclinations are equally prevalent among later dykes, with a slight relative increase among the N.E. dips as compared with the total number of fissures.

	North and west of Central Complex of SKYE, including Harris			South and east of Central Complex of SKYE, excluding Scalpay 2nd. swarm			ARDNAMURCHAN			SMALL ISLES		
	DIRECTION OF DIP OF THE DYKES											
	N.E.	V.	S.W.	N.E.	V.	S.W.	N.E.	V.	S.W.	N.E.	V.	S.W.
No. of dykes involved in multiple-intrusions	163	162	103	608	157	114	10	8	4	22	37	20
No. of multiple-intrusions	69	68	40	232	60	42	5	4	2	8	17	10
No. of dykes pll. to pre-existing dykes	94	94	63	376	97	72	5	4	2	14	20	10
Ratio of dykes pll. to pre-existing dykes	1·49	1·49	1	5·22	1·38	1	2·5	2	1	1·4	2	1
Total no. of fissures (multiple or single)	686	805	582	1326	715	408	147	120	44	384	336	263
Ratio of total no. fissures	1·18	1·37	1	3·25	1·75	1	3·34	2·73	1	1·46	1·28	1

In Ardnamurchan, on the other hand, later N.E. dips became proportionately less, and later S.W. dips proportionately more, dominant than in earlier periods. In the Small Isles the only significant change is that later vertical dykes became more prominent.

The corresponding analysis for the dykes of the Scalpay Secondary-Swarm is shown below. Again, an increase among N.E.-dipping later dykes is evident, with a proportionate decrease among vertical inclinations.

	N.E.	V.	S.W.
(The columns	44	24	16
of this table	19	10	7
correspond to	25	14	9
those of the	2.77	1.56	1
table above.)	160	199	102
	1.57	1.95	1

Unfortunately with an analysis of the type detailed in the two tables above it is impossible to separate entirely the purely local control exerted by the dip of an earlier dyke on a later dyke from a changing regional control. The results of the analysis appear to indicate, however, that the regional controls have suffered some changes, and that the influences of earlier dykes could not countermand these changes, since if they had been able to do so the ratio of dykes parallel to pre-existing dykes would have been the same as the ratio of the total number of fissures. One additional point arising out of the above analysis is the somewhat different behaviour of the later dykes of Ardnamurchan and the Small Isles, compared with the dykes of the Skye-Swarm. This behaviour emphasizes yet again either a different age for these swarms or their subjection to a different structural control.

(c.) The Influences of the Foliations and Joints in the Country-Rock and the Control Effected by the Structure of the Lava-Pile of northern Skye. The parallelism of dykes intruded into the Moinian rocks to the strike of these rocks, and sometimes also to the dip of their foliation, is especially prominent in the region from Mallaig to Loch Sunart. The less well-developed parallelism of the trend and dip of the dykes with the orientations of the strike-slip joints is observed especially in Applecross, Raasay and Soay, but is not as marked in southern Skye and Rhum. Concerning both these groups of dykes the problem, which is rarely stated by other authors, is one of interpretation of what is really controlled — the surficial dyke or something at greater depth. At present, however, it is difficult to assess the relative importance of a superficial control on the trend and dip of the dykes and of perhaps a more fundamental control at depth of the form and disposition of the body of magma from whence the dyke material arose (but see Ch.16:V).

The "controls" on: (i.) the trends of the dykes in the lava-pile of northern Skye, and (ii.) the dips of the dykes wherever they outcrop in the lavas, i.e. also in the Small Isles, have been mentioned in the previous chapters. Only general correlations can be made between the form of the lava-trough and the "fanning" of trends or symmetrical disposition of N.E. and S.W. dips about its axis, on the E.N.E. and W.S.W. sides, respectively. The dips of both lavas and dykes are especially complicated by the extensive late-Tertiary block-faulting.

(d.) The Controls of Pre-existing Faults and Fractures. Coincidence of dykes with faults is found in the lava-pile of northern Skye. In Morvern, Moidart, Ardnamurchan, and Sunart, in a variety of rocks (Moine schists, Strontian granite, lavas, and the Central Complex of Ardnamurchan) dykes are parallel to N.W. faults of Tertiary age. The N. to S. faults in the same districts are possibly of younger date (MacGregor,1967,p.10), and Tertiary dykes coincide with these in the area from western Ardnamurchan to Strontian. MacGregor concluded that an E. to W. relief of pressure took place in late Tertiary times. Joints of the same trends as the faults, and possibly genetically related, are also said to be followed by the dykes in some cases.

Auden (1954) advanced certain hypotheses on the significance of fracture-patterns in north-western Scotland. A reproduction of part of his map is presented as fig.124. The lines on the map are related to the topographic features of the area; some are zones of shattering or faulting confirmed by field-work, whilst others are deduced without such confirmation. No attempt to differentiate between fractures with or without net displacement was made. Auden's

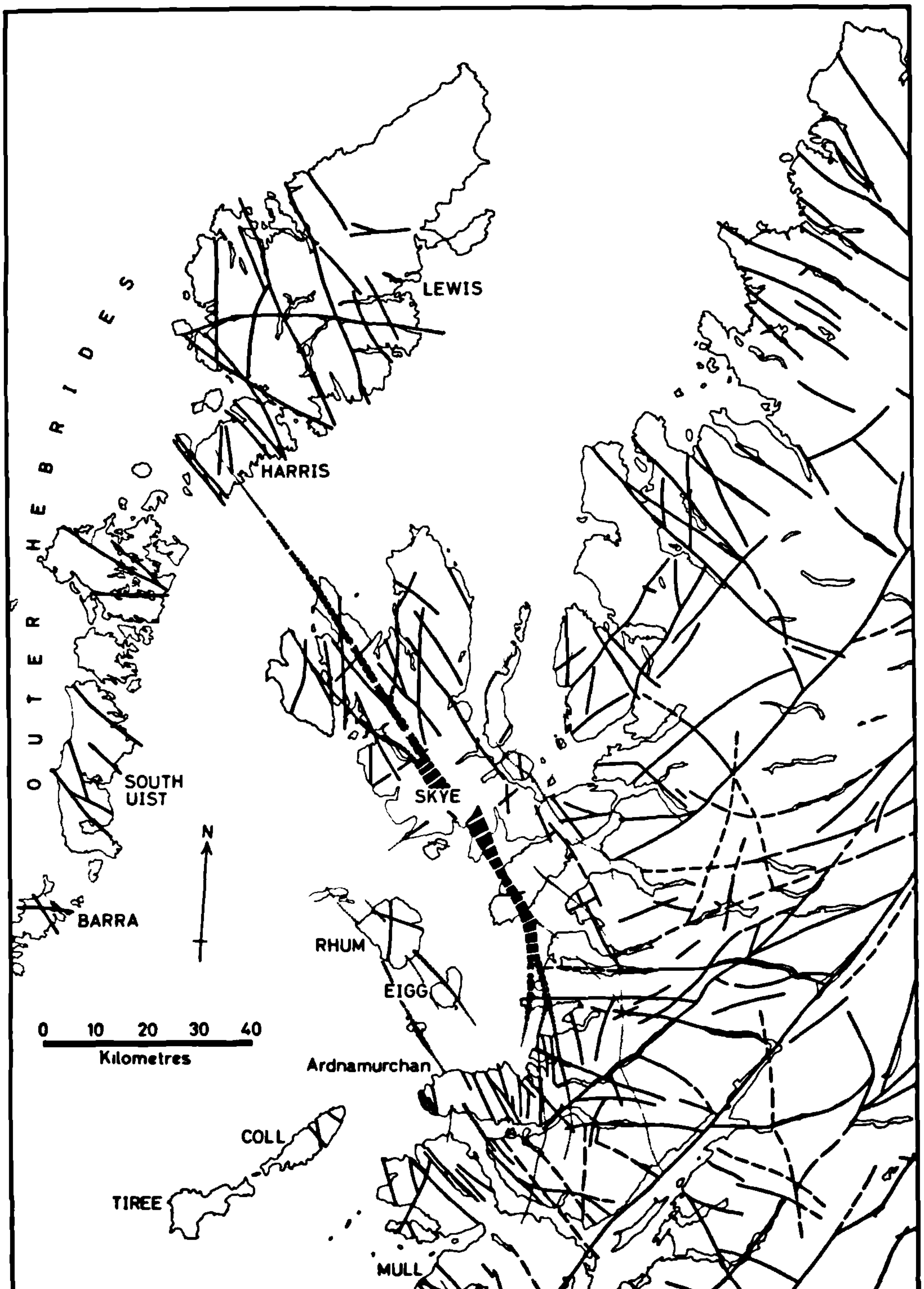


Fig 124. Fracture Zones in North-West Scotland (after J B Auden, Geol Mag, xci, 342), with addition of the axes of dilation (broken and tapering lines)

conclusions are presented in the following two paragraphs.

A system of Tertiary fractures (N.W. to S.E. and N. to S.) was superimposed on the rhombic pattern of the late-Caledonian faulting (N.E. to S.W. and E. to W.). The N.W. to S.E. fractures in the Western Isles, including the Outer Hebrides, and in Ardnamurchan, are of Tertiary age. The N. to S. fractures in north-western Skye, eastern Ardnamurchan and Rhum are undoubtedly Tertiary, and the N. to S. fractures in Lewis and Applecross are probably of the same age.

On the mainland from Knoydart to the Great Glen Fault, there is a radial pattern of fractures converging on a central point near Eigg. Three curving fractures from Loch Linnhe swing towards this same central point. Furthermore, the coastlines of Ardnamurchan, Moidart, Morar, and Knoydart, as well as certain arcuate fractures in these same districts, are concentrically disposed to this central point. Auden suggested that these fractures may be linked to an igneous centre with a buried plutonic phase (under Eigg or the sea). This was, Auden argued, the first Tertiary centre to form and involved the crust in radial and peripheral fractures which may have eased the strain for the development of the centres of Skye, Rhum, Ardnamurchan, Mull, and Arran. He added that when the main dyke-swarms were formed, a single direction of strain relief in the crust was completely independent of the earlier directions of fractures. The N.N.W. to S.S.E. line joining the Central Complexes from Rhum to Arran may have acted as a line of weakness during the early stages of central igneous activity. Some time later a set of fractures oblique to the co-central line had developed.

It is proposed that Auden's Tertiary centre at or near Eigg is one and the same as that located by the present author, by perhaps more accurate techniques, lying off the south coast of Muck and here called the "Muck centre". It must be added, however, that there is no evidence to be gathered from the structure of the dyke-swarms that this centre was necessarily the first to form. Moreover, there is notably no observed development of dyke-swarms radially or concentrically disposed about this centre.

15:IV. The Broader Structural Setting of the Dyke-Swarms : their Relationships to the North Atlantic Tertiary Province.

The Tertiary volcanic districts of Scotland and northern Ireland constitute only a small part of the North Atlantic Tertiary Igneous Province (fig.125). In Greenland, Iceland, Jan Mayen, the Faeröes, Rockall and St. Kilda, there are exposed sites of Tertiary volcanic rocks. Evidence from sea-bottom dredging, seismic refraction techniques, topographic features of the sea-floor, and gravity and magnetic anomalies (e.g. Donovan,1968; Roberts,1970) reveals the possible existence of many more sites throughout the whole of

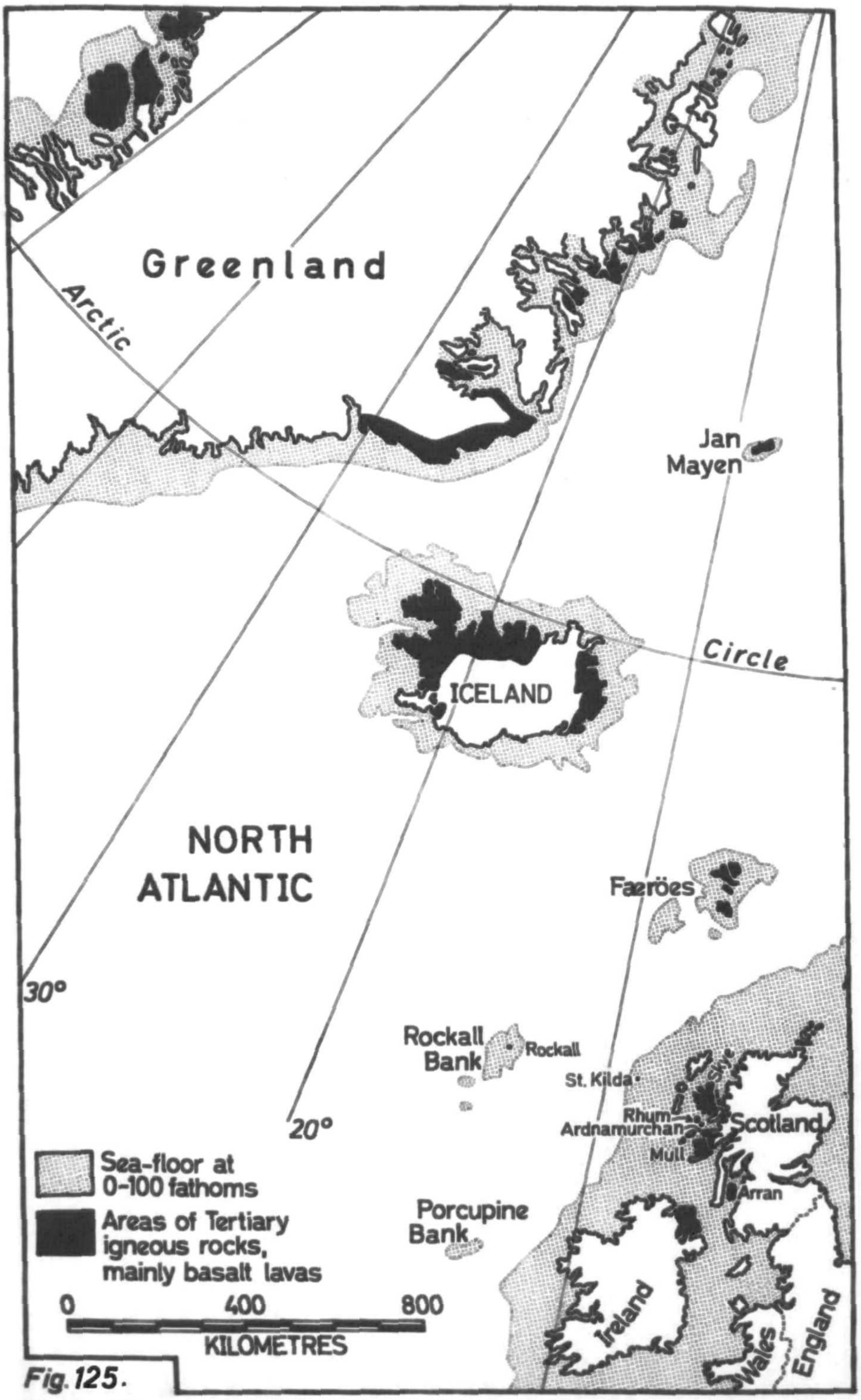


Fig. 125.

North Atlantic (or Thulean) Tertiary Igneous Province. (Taken from: fig.17, British Regional Geology, Scotland: The Tertiary Volcanic Districts, H.M.S.O., 1961.)

the North Atlantic (fig.126).

Current opinion, then, is that there was a large number of centres of volcanic activity (e.g. Anderson & Dunham, 1966,p.79), than that the present outcrops of the lavas are but remnants of a single North Atlantic lava-plateau. Many authors believe that these lavas of the Thulean Province are of fissure-fed type. The Columbia Basalts, the Deccan Traps, the Stormberg Lavas including those of the Lebombo Range and the Karroo Dolerites, and the late Precambrian Keweenawan Basalts are likewise commonly thought to be fissure-fed. Evidence in favour of the existence and function of feeder-dykes has been derived from observations of (i.) the actual freezing of magma in a fissure to form a dyke as it took place (Stearns & Clark,1930), and (ii.) connexions of dyke-feeders to lavas, e.g. in the Faeröes (Walker & Davidson,1936), and in northern Ireland (Patterson,1950; G.P.L. Walker,1959A,p.196) and Iceland (G.P.L. Walker,1959B; 1960; 1964,p.355).

Tyrrell (1937,pp.109-10) drew an analogue between the Tertiary Hebridean swarms and the rift zones of Hawaii, stating that flood-basalts are due to the combined operation of shield-volcanoes and, after cauldron-subsidence, fissure -eruptions. Agashe and Gupte (1968,pp.310-3) also postulated such a dual source for parts of the Deccan Traps. Tyrrell (1937,p.106) remarked that multiple-dykes may be manifest-

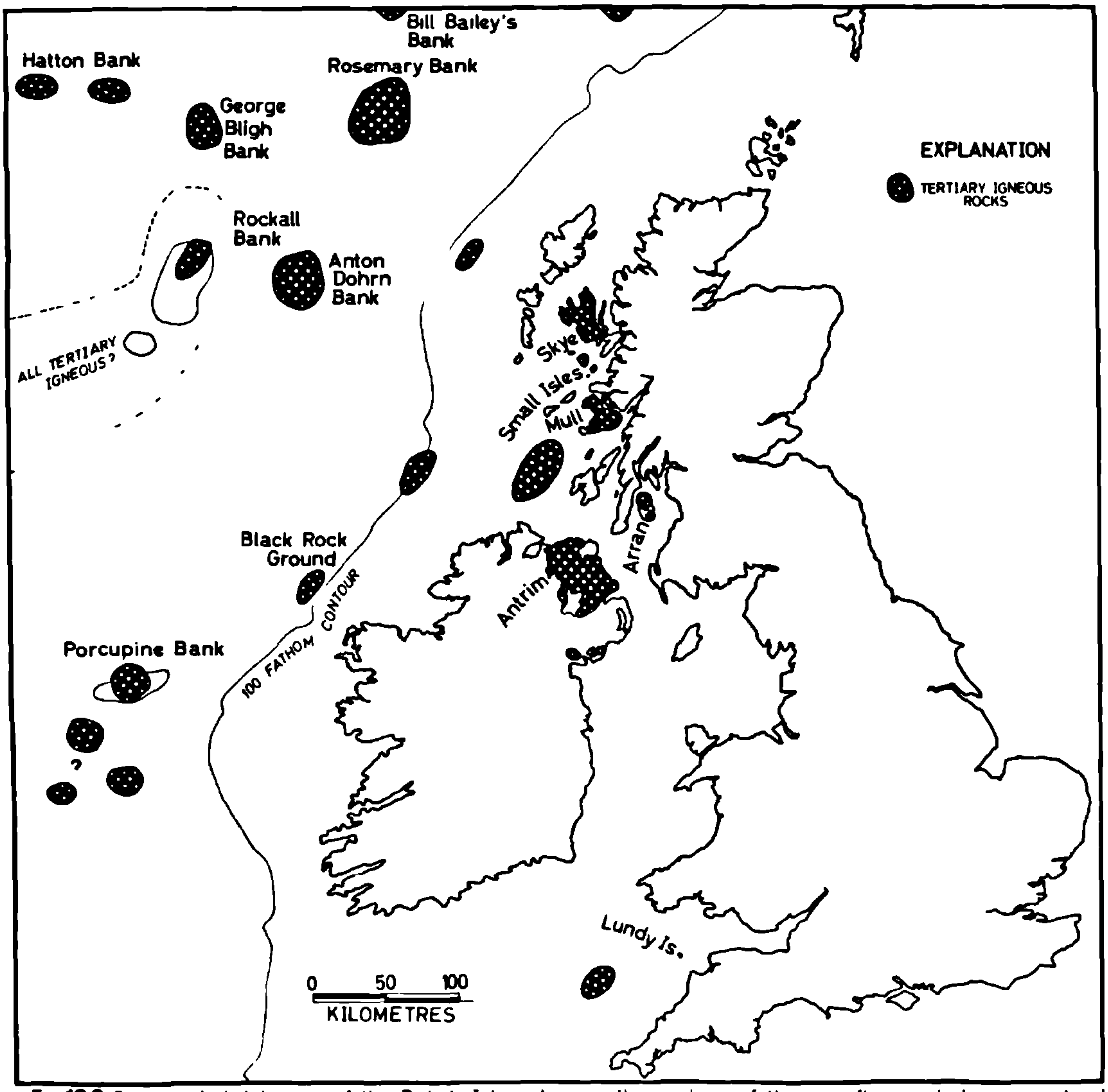


Fig.126. Geological sketch-map of the British Isles showing the geology of the sea-floor including conjectural submarine outcrops. (After Donovan, 1968, fig. 7)

ations of the actions of more than one pulse of magma along a fissure-feeder. Multiple-dykes are a remarkably common feature of the Skye-Swarm (Ch.8:II & III).

Since dyke-swarms are found throughout the exposed volcanic districts of the Thulean Province, and quite possibly exist in the neighbourhoods of submerged seamounts in the North Atlantic, it is tempting to postulate that a composite lava-plateau did extend almost continuously across the North Atlantic. Such a hypothesis would require that fissure-feeders associated with adjacent centres issued lava-flows which merged together.

In the following chapter the origin of, for instance, the Skye-Swarm cannot then be considered in isolation. A discussion of the relation of the dyke-swarms in the Area of Study to the volcanotectonics of the entire north-east Atlantic indicates that, in some respects, the hypothesis of a composite Tertiary lava-plateau is not entirely untenable, since such a single unit could have existed before the break-up of the north-east Atlantic.

Chapter Sixteen

THE ORIGIN OF THE TERTIARY DYKE-SWARMS OF SKYE, ARDNAMURCHAN AND THE SMALL ISLES (and other Tertiary Dyke-Swarms in Britain)

16:I. General Introduction and Review of Former and Current Opinions on the Origin of Dyke-Swarms.

It is clear from a study of the work of earlier researchers that no single mechanism can be assigned to the formation of all the dyke-swarms of the world. The structure of any dyke-swarm is largely controlled by the local tectonic environment in which that swarm was developed.

Some authorities argue in favour of the theory that tensional forces, responsible for the growth of feeder-dykes and associated flood-basalts, are the result of elastic rebound after orogeny (e.g. Fahrig & Wanless,1963). De Boer (1967) supposed that the Mesozoic dyke-swarms of the Appalachians were emplaced during just such a post-orogenic release of compressive stress. Other post-orogenic swarms thought to have been emplaced in tensional environments and trending parallel to the prominent grain of the preceding orogeny include the Caledonian dyke-swarms of Scotland (Richey,1939) and of the Ards Peninsula (Reynolds,1931), the dykes of north-eastern South Island, New Zealand (Challis,1961), the Independence Dyke-Swarm of eastern California (Moore & Hopson,1961), and the Beartooth Dyke-Swarms (Prinz,1965).

Clifford (1968), on the other hand, was of the opinion that many regional swarms and their associated lava-flows indicate tensional forces due to motions in the mantle.

He drew an analogy between the Mid-Atlantic Ridge and the plateau-basalt provinces of the world. In the Mid-Atlantic Ridge displacements of up to 400km. away from the rise-ridge system are associated with the intrusion of dykes and extrusion of basalts. Clifford supposed that in the plateau-basalt provinces of, for example, the Darwin Rise, Siberia, Stormberg-Karroo, and the Deccan, as well as the dyke-swarm districts of the Canadian Shield, tensional zones of continental proportions were developed due to sub-crustal flow in convection cells analogous to the flow at mid-ocean ridges. Each province and associated dyke-swarm was situated over a convective updraught, implying that each dyke-swarm overlay a zone of crustal separation.

In other cases, authors have said of the origins of particular dyke-swarms that they were initiated by crustal flexuring (du Toit,1930), or formed simultaneously with such flexures (Wager & Deer,1938). Where dykes are at their most prolific in the western Deccan, high positive gravity anomalies and steep gravity gradients are attributed (West,1959) to upwarps of the lower crust, such upwarps acting as foci of lava-extrusion and presumably also of dyke-intrusion.

The relationship of dyke-swarms to volcanic centres has influenced the opinions of some workers on the origins of such swarms. Speight (1938) believed that the source of the swarm of dykes radially-oriented around the volcanic cone of Lyttelton (New Zealand) was a subcrustal reservoir, and he supposed that the injection of several dykes was synchronous with each phase of doming of the cone preceding the eruption of every lava. G.P.L. Walker (1964) attributed the high dyke-intensities (10 to 20 per cent.) near Icelandic Tertiary volcanic centres to the existence of points of crustal weakness below the centres, which could at each centre be in the form of a high-level intracrustal magma cupola.

Certain dyke-swarms are apparently of syn-orogenic formation, e.g. the dykes of Stjernoy in north-west Norway (Ramsay & Sturt,1970).

Odé's (1957) mechanical analysis of the Spanish Peak radial dyke-swarm indicated to him that a symmetrical regional stress-field was superposed over a local stress-field at the time of dyke-injection. The local stresses were supposedly caused by the fluid pressure of the magma rising vertically at West Spanish Peak. R.B. Johnson (1961), however, pointing out that Odé's analysis required a simultaneous origin of all the radial-dykes, gave evidence that there was not one but several different such magmatic phases. Johnson thus implied that the Spanish Peaks is not a true example of a radial-swarm.

Finally, some workers have turned their attentions to the influences of pre-existing structures within the basement (e.g. Hills,1952), or of higher level crustal rocks (e.g. R.B. Johnson,1961; Carruthers et al.,1932), on the evolution of dyke-swarms. Hills stated that the fractures occupied by the Wood's Point Dyke-Swarm are related to a horizontal torsion, due to differential advance of basement folds.

16:II. Review of the Views of Other Researchers on the Origin of the British Tertiary Dyke-Swarms.

As equally varied as those hypotheses reviewed above are the proposals for the origin of the Skye, Ardnamurchan, and Small Isles Tertiary Dyke-Swarms.

Geikie (1897B, Chapter XXXV) stated that the regularity of the trend of the dykes, despite the diversities of the structure, resistance, and elasticity of the country-rock which they intruded, is indicative of a source at great depth. The mechanism of formation of the dykes was a repeated operation over a long period of time. Following the views of Hopkins (1839,pp.69-71), who treated the problem of the emplacement of dyke-swarms mathematically, Geikie envisaged a great horizontal tension in the earth's crust over the area occupied by the swarms.

Harker (1904,p.412) considered that in the first half of the Tertiary volcanic period the earth's crust was in a state of continuous or spasmodic strain. This strain consisted of a uniform (in time and degree) and geographically extensive (or regional) component and of localized components which developed in certain areas and at certain times at particular centres of disturbance.

Evans (1925,p.xcviii), commenting on the supposed tilting of the lavas of Skye towards the west, attributed this movement to a possible flow in zones lying beneath these lavas. This flow was towards the east, dragging the base of the lavas along with it, and was apparently "the direction of the flow of the magmas which formed the major intrusions". The N.N.W.-trending dykes and N.E.-dipping faults also imply a drift from W.S.W. to E.N.E. of the surface blocks (Evans,1925,p.ci). This stretching or slow flow of the presumably plastic zone beneath was supposed, by Evans, to be the immediate cause of the minor fissuring of the crustal rocks.

Thomas (1927,pp.51-2) attributed the greater intensities of dykes in the vicinities of the Tertiary plutonic complexes to the greater facility of such regions to fracture and their possible subjection to greater tensile stresses than in the adjacent country-rock. Such intense fracturing was possible where tensional stresses acting on a thin crust were tangential to the upper surface of a reservoir filled with liquid or plastic material.

Rastall (1931,p.124) said that the N.W. trend of the Tertiary dykes of Britain is due to the influence of the

N.W. to S.E. strike of the Lewisian basement, which he said may underlie Britain northwards of the Bristol Channel and the Thames, and may even be traceable into Cornwall.

In 1930, Thomas (Richey & Thomas,1930,p.54) remarked that the alignment of the Central Intrusive Complexes of the British Tertiary region along a roughly N. to S. line, which passes along the western coast of Scotland and the eastern coast of Ireland (fig.1), indicates a line of crustal weakness. Thomas observed that this line is "unrelated to the direction followed by the majority of the dykes that form the respective swarms". Richey (1932,pp.125-6), however, noted that the N. to S. dykes found on the north coast of Ardnamurchan, in Raasay and Applecross coincide in trend with this zone of crustal weakness.

Richey (1939,p.431) postulated that magma chambers of elongate form underlay the areas where dykes of any particular age are found. Uplift, caused by a change from the solid to the liquid state of this elongate body causing its expansion, would create an elongate up-domed structure, resulting in a tension in the roof-rocks, which would extend throughout their whole thickness. Dyke-intrusion would follow along tensile cracks in a central zone parallel in trend to this elongate dome.

On partly similar lines to Richey, F. Walker (1961) postulated a deep-seated, extensive, stratiform source-magma reservoir for the Islay-Jura Swarm, and Charlesworth (1963) envisaged as the source of the Tertiary dykes of Ireland the existence of a sheet-like reservoir at different levels from 25 to 50km. below the surface.

16:III. Introductory Remarks to the Proposed Origin of the Tertiary Dyke-Swarms of Britain.

At the present time, the geographical distributions of the Tertiary dykes are certain only for the swarms described in this thesis and for the Mull-Swarm (Sloan,1970), although, with what few details there are for the other swarms in Britain and Ireland, a general idea of the positions of the dilation-axes of these can be deduced (fig.127). The dilation-axes are represented by heavy lines, the thicknesses of which are not proportional to the intensity of the dykes (cf. fig.48). The broken lines represent in some cases uncertain positions and in others uncertain existences of some axes. There are perhaps too many axes depicted for northern Ireland, considering that the intensities of the swarms there are much lower than those of Skye and Mull.

Each Central Intrusive Complex is "connected" by a dyke-swarm to a neighbouring Complex (fig.127). This is certainly true for Skye, Ardnamurchan, Rhum, and Arran and Mull, and there is little doubt that the Islay-Jura Swarm merges with the Arran and northern Ireland Swarms. The Lundy Swarm alone is in a unique position, far-removed from the

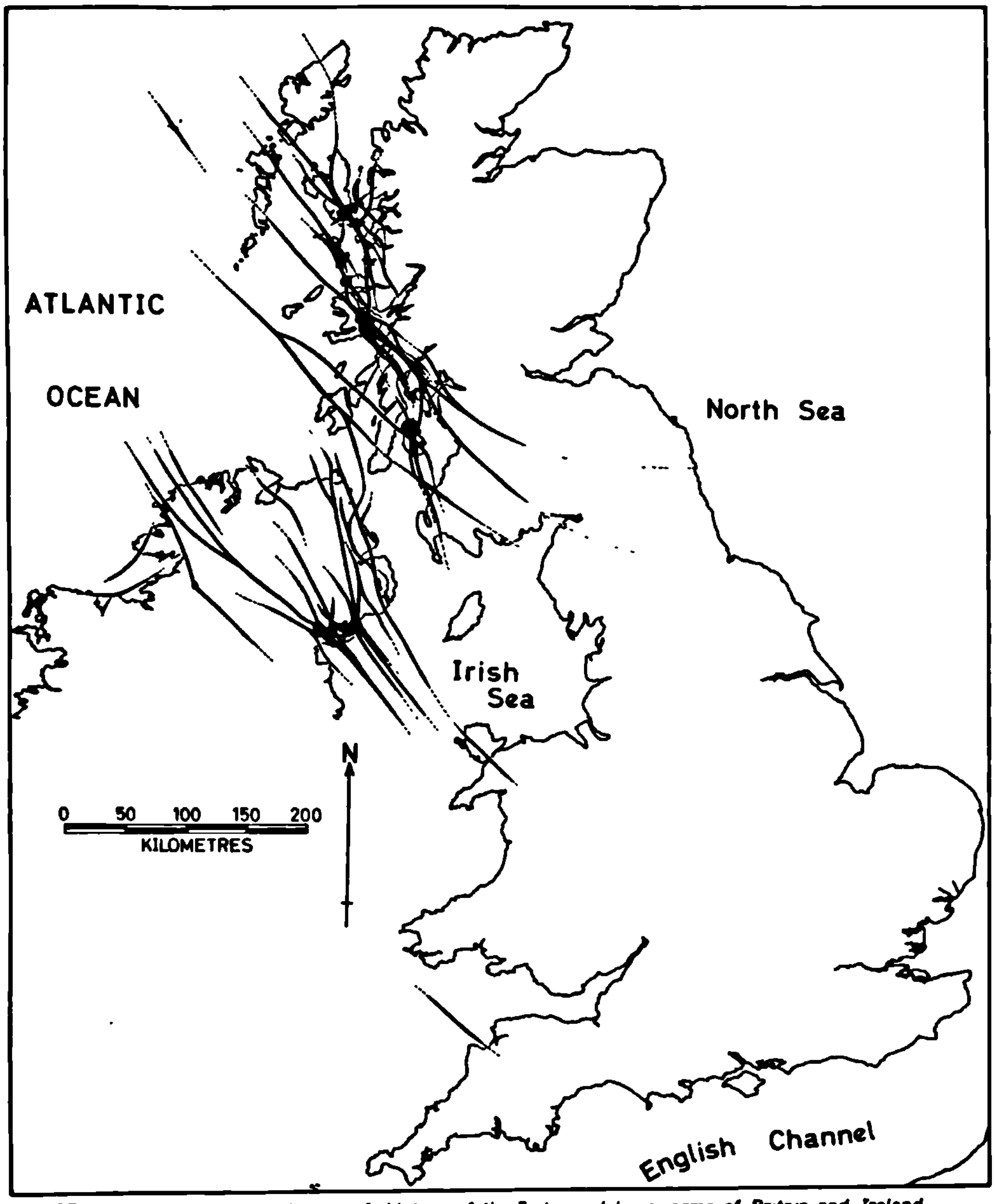


Fig.127. Known and postulated axes of dilation of the Tertiary dyke-swarms of Britain and Ireland Distribution of axes in Ireland is based on an interpretation of fig 1, Field Excursion Guide to the Tertiary Volcanic Rocks of Ireland, International Association of Volcanology and Chemistry of the Earth's Interior, 1969, by C.H.Emeleus and J.Preston Distribution of axes of the Mull-swarm is based on work by T.Sloan, Ph.d. Thesis, Lond., 1970. Axis of the Lundy-swarm is derived from work by A.T.J. Dollar Other axes are based on work by J.E.Richey, and on an interpretation of the 1 in. to 1ml sheets of the Geological Survey of Scotland

nearest neighbouring swarm. The dyke-swarms show a decrease in their overall intensity from Skye, to Mull, to Arran, to Mourne-Carlingford, to Lundy. Apart from the somewhat anomalous behaviour of the dyke-intensities of the swarms of the Small Isles, Ardnamurchan, and Islay-Jura, the general decrease of dyke-intensity from north to south might be related to an increased depth in this direction of the source-magma.

The dykes which constitute the subswarms "connecting" the present locations of the Central Intrusive Complexes, i.e. the Broadford Bay-Applecross Subswarm and the Rhum-Subswarm, possibly predate most of the dykes of the various other types of swarm in the Area of Study (Ch.7:VIII, 11:VI). The fact that such dyke-swarms are largely of N. to S. trend apparently confirms the similar views of Richey (1939) and Auden (1954) that early N. to S. lines of weakness existed in the area at the commencement of dyke-emplacement.

However, despite the possible different ages of the main, secondary, and subsidiary swarms of the dykes not only of Skye, but also of Ardnamurchan and the Small Isles, the variation of the petrographic types within any one of these types of swarm, especially the main regional linear types, seems to indicate a long period of intrusion for each of the swarm-types. The main linear-swarm of Skye is of an especially long interval of intrusion. Nevertheless, the dilation-axes, as mentioned earlier (Ch.7:XI), appear to have remained in fixed and constant positions. If there was a change of the conditions governing, for instance, on the one hand the intrusion of the N.E.-subswarms, and on the other the intrusion of the N.W.-swarms, then this must have been rapid, for such swarms are of distinctive trends and specific intensity-distributions which merge but little one into the other. It seems more likely that some constant tectonic control was operative during the emplacement of both regional linear-swarms and subswarms (Ch.7:XI).

16:IV. The Concept of Ridges of Basaltic Magma Underlying the Tertiary Dyke-Swarms of Britain.

As will become clear in later sections of this chapter, the author has reason to believe that, with some modifications, the proposal put forward by Richey (1939) for the origin of the dyke-swarms is plausible. Richey believed that the constant control on the evolution of the Hebridean dyke-swarms may have been in the form of a deep-seated, elongate and axially up-domed sheet of basaltic magma. Thomas (1927,p.45) at an earlier date had explained the distribution of the Tertiary Hebridean plateau-lavas on the same basis of an intracrustal magma-reservoir. Of the same opinion as Richey were, as mentioned above, Charlesworth (1963) and F. Walker (1961). Foster (1958), too, envisaged an elongate magma-source at the base of the Teanaway Dyke-Swarm.

On the broad lines indicated by Richey, a model (fig. 128) was constructed to illustrate the probable form of an elongate body of magma underlying the Area of Study. The form of this markedly ridge-like body is perhaps of greater vertical extent than that proposed by Richey. Its dimensions are based on the information in fig.47 (in pocket). The height of the ridge at any point, above a planar surface at a depth of 15km. (Ch.12:III), is proportional to the dilation at the site in the present level of erosion lying vertically above that point. The acuteness of the ridge is proportional to the rate of decrease of dilation away from (at right-angles) the corresponding dilation-axis.

The basic material at shallow depth (less than 1km.) beneath the Red Hills (McQuillin & Tuson,1965) is not represented on the model, since the method of construction precludes this. Unfortunately the method of construction adopted also caused the production of a very pronounced ridge reaching upwards to very shallow depths near the Central Complex of Skye. The author does not believe that this quite so shallow depth is feasible, and succeeding discussions elucidate this opinion. An alternative model with the proposed "Muck centre" is depicted in fig.129.

Dykes were fed by the ridge of magma and became more prolific at its higher and more acute portions, attaining the intensities of a dyke-complex (Ch.4:XIV). Dyke-complexes

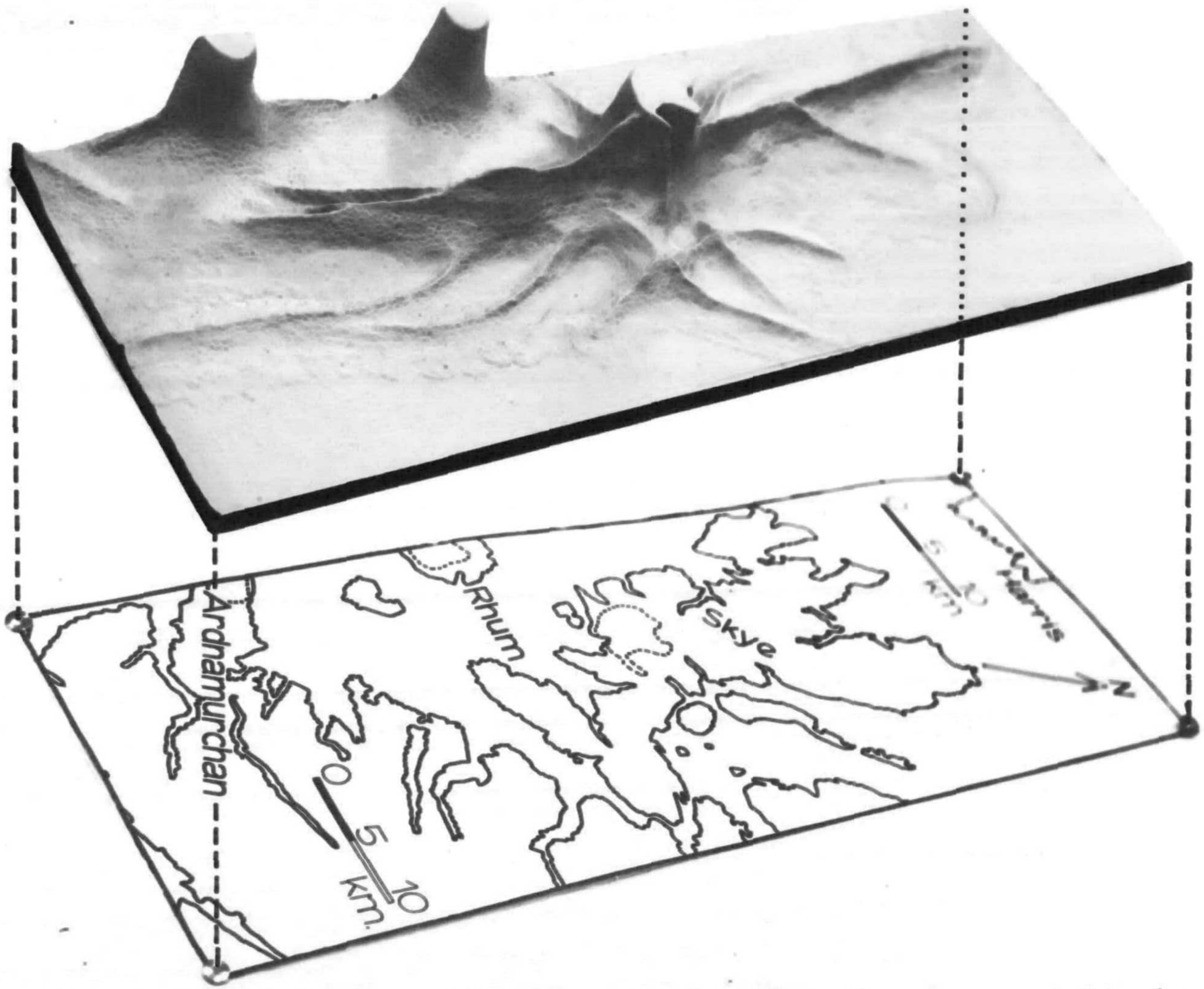


Fig.12X.The form of the basaltic ridge underlying the Area of Study

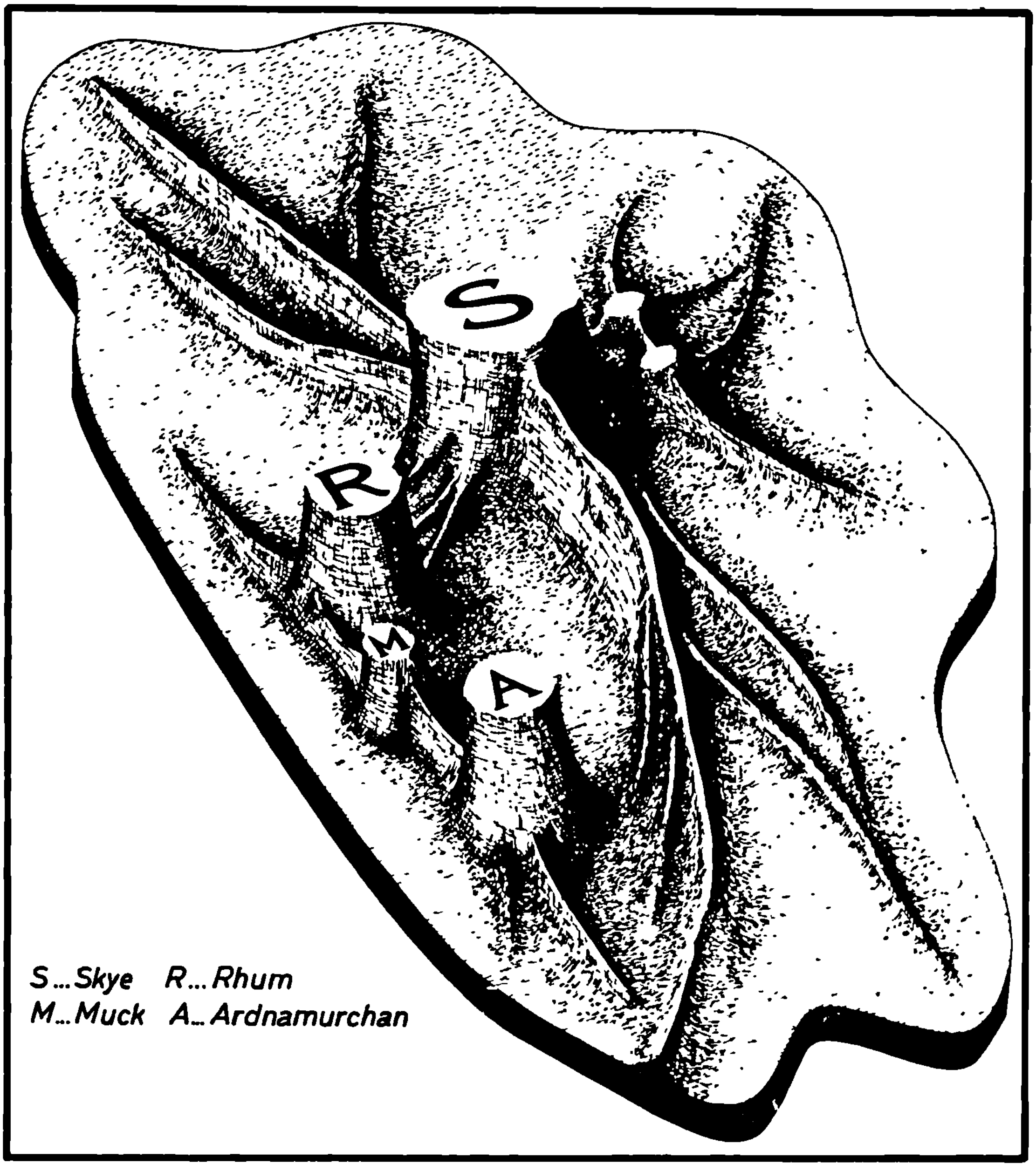


Fig.129. The Form of the Basaltic Ridge underlying the Area of Study (Muck included)

are found in an analogous situation in Hawaii at or near the crest of the Hawaiian Ridge (Wentworth & MacDonald, 1953,p.89; Malahoff & Woollard,1968; also Ch.12:II). The Teanaway Dyke-Swarm of Central Washington is so dense in parts that it covers 90 per cent. of the land-surface (Foster,1958), and perhaps a ridge of magma lies at no great depth beneath.

16:V. Relation of the Trends of the Dykes in the Area of Study to the Forms of the Basaltic Ridges.

Any proposed mechanism of origin of a dyke-swarm must satisfy the available evidence on not only the amount of crustal-stretch but also on other properties of the swarm, and most especially its trend-distribution. In this latter context it may be profitable to attempt a simplification of the geographical variation of the trend of the dykes, to fit as closely as possible some simple mathematical model. Some possible trend-distributions conceived by the present author are shown in fig.130.

The geographical distribution of the arithmetic-average trend (figs.12,13,42,&122) most closely agrees with the hypothetical distribution of fig.130E. Account must be taken, however, of the spread of the trends at any one locality. The geographic distributions of "Normal" dyke-trends (Ch.6:V), as well as "Normal" dyke-thicknesses (Ch.9:II), indicate that not only the lava-pile but also the underlying magma-

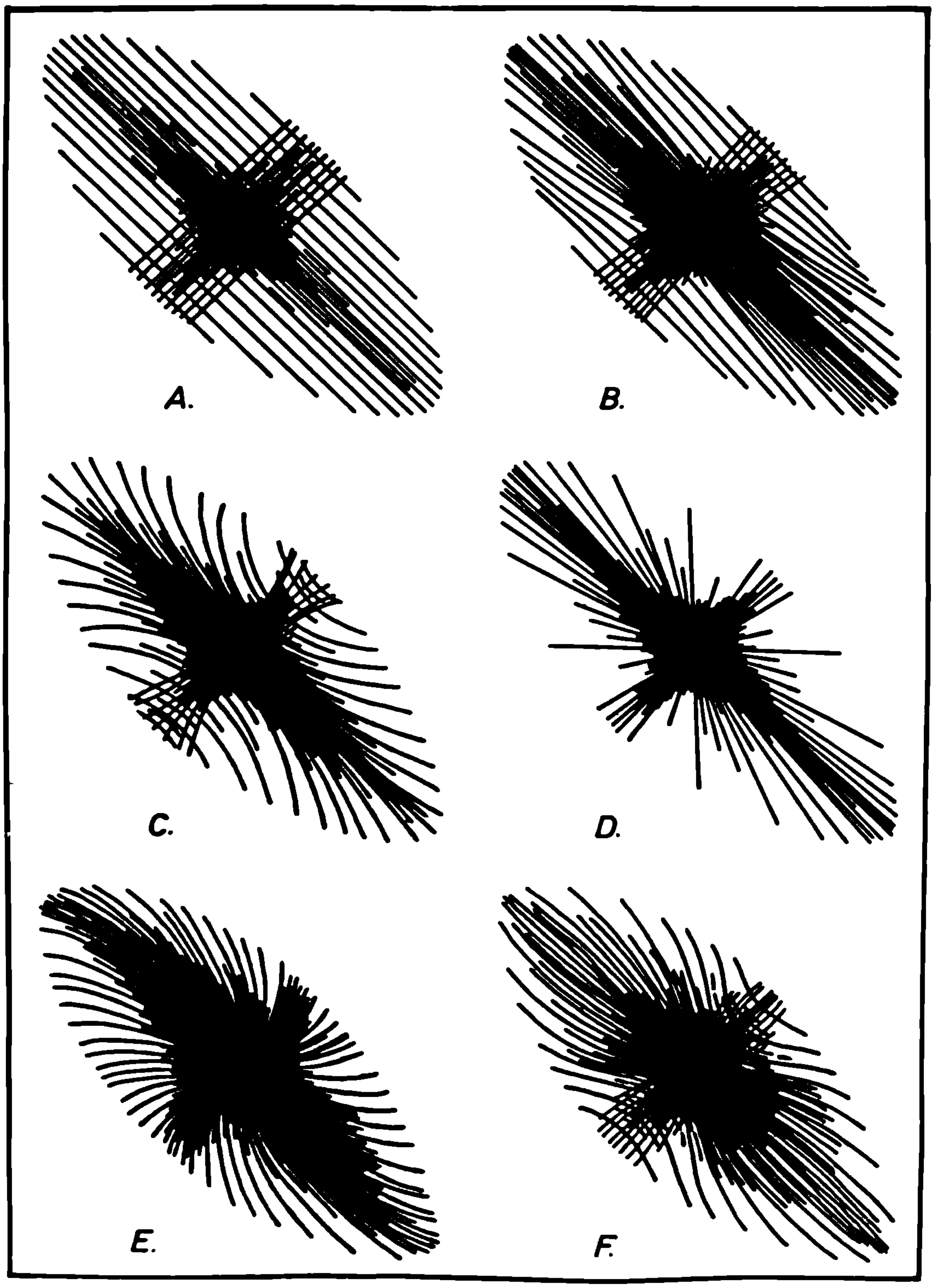


Fig.130. Some hypothetical trend-distributions of dyke-swarms.

ridge exerted some control on this "Normality".

Price and Ramsay (pers. comm.) suggested that not only the fact that the trends of the dykes "fan" in the lava-pile (on arithmetic-average), but also the fact that within groups of dykes at the sites of the dilation-axes (e.g. Group '2' in Appendix 6; and fig.122) there are a variety of trends, indicate the influence of transverse displacements in the crustal rocks in the neighbourhood and parallel to the basaltic ridge. A sinistral transcurrent displacement may give rise to a variance in trend of individual dykes in the horizontal direction, such that each dyke may have a sigmoidal outcrop of the type shown in fig.130E.

Unfortunately the outcrops of dykes cannot be traced for great distances, but the general configuration of the trends of the dykes as a whole is roughly sigmoidal (fig. 130E). The "fanning" of the trends of the dykes in the lava-pile of northern Skye, the N. to S. dykes of Applecross and Morar, and the Broadford Bay-Applecross Subswarm of variable trend, are all in part reflected in the configuration of fig.130E. One of the greater problems of interpretation of the distribution of the trends of the dykes, however, is the interference between the Scalpay Secondary-Swarm and the main regional linear-swarm of N.W. dykes, each with its associated splay of dyke-trends. If the development of parts of the swarm illustrated in fig.130E is emphasized, and certain parts suppressed, e.g. by the superimposition of a regional N.E. to S.W. relative tension on to the sinistral strike-slip displacements, then distinct north-westerly and conjugate north-easterly swarms may be produced simultaneously under these combined systems of stresses, with dykes of intervening trends (between N.W. and N.E.) in a minority.

The N. to S. and N.E. (and even E. to W.) dykes of regions such as Morvern (Bailey & Wilson,1924,p.359) and Cowal (Clough in: Gunn et al.,1897), lying between adjacent Central Intrusive Complexes, can now be interpreted in a similar fashion to the dykes of Applecross and Morar, i.e. as a part of a sigmoidal splay of trends about the respective Central Complexes.

Accordingly, Richey's (1939,p.432) opinion that "oblique fissures" (i.e. those dykes with trends fanning about the axis of the swarm) were formed laterally to the ridge of magma as a result of torsional stress due to the uprise of this ridge, is modified by the present author. The ridge of magma did not control the dyke-trends: rather the form of the ridge and the dyke-trends alike were results of the same causes, that is the sinistral transcurrent displacements. The generation and uprise of the magma of the ridge might be genetically related to a pressure release in the upper mantle and overlying crust, consequent upon the transcurrent movements. In any case movement of a fractured crust would have created, as Williams (1953) said, a potential void favourable to the rise of magma.

16:VI. Evidence to Substantiate the Proposed Origin of the Tertiary Dyke-Swarms of Britain.

There are certain facts, additional to those relating to the geographical distribution of the trend of the dykes, which are in corroboration of the postulated mechanism of origin. These facts are in sections (1.) to (8.), below:-

(1.) Camasunary Fault. During a period of late-Cretaceous or early-Tertiary tectonism the Camasunary Fault and other similar faults were developed (probably pre-upper Cretaceous). The Camasunary Fault (fig.131) has at least a 300m. and perhaps 600m. downthrow (Wedd in: Teall,1902,p.147) towards S.E., and trends roughly N.E. to S.W. It passes perhaps off the east coast of Rona, through Raasay (first mentioned by Judd,1878,pp.671-2), and presumably beneath the lava-pile on Skye. Its outcrop re-emerges at Camasunary (head of Loch Scavaig), but its line is considerably displaced by some means. It has been suggested that such displacement is due to a forceful intrusion of the Red Hills Granite (Anderson & Dunham,1966,pp.174-5). The fault passes S.S.W. from Camasunary between Eigg and Rhum (Wedd in: Teall,1902,p.147; Wedd in: Peach et al.,1910,pp.9,150-1).

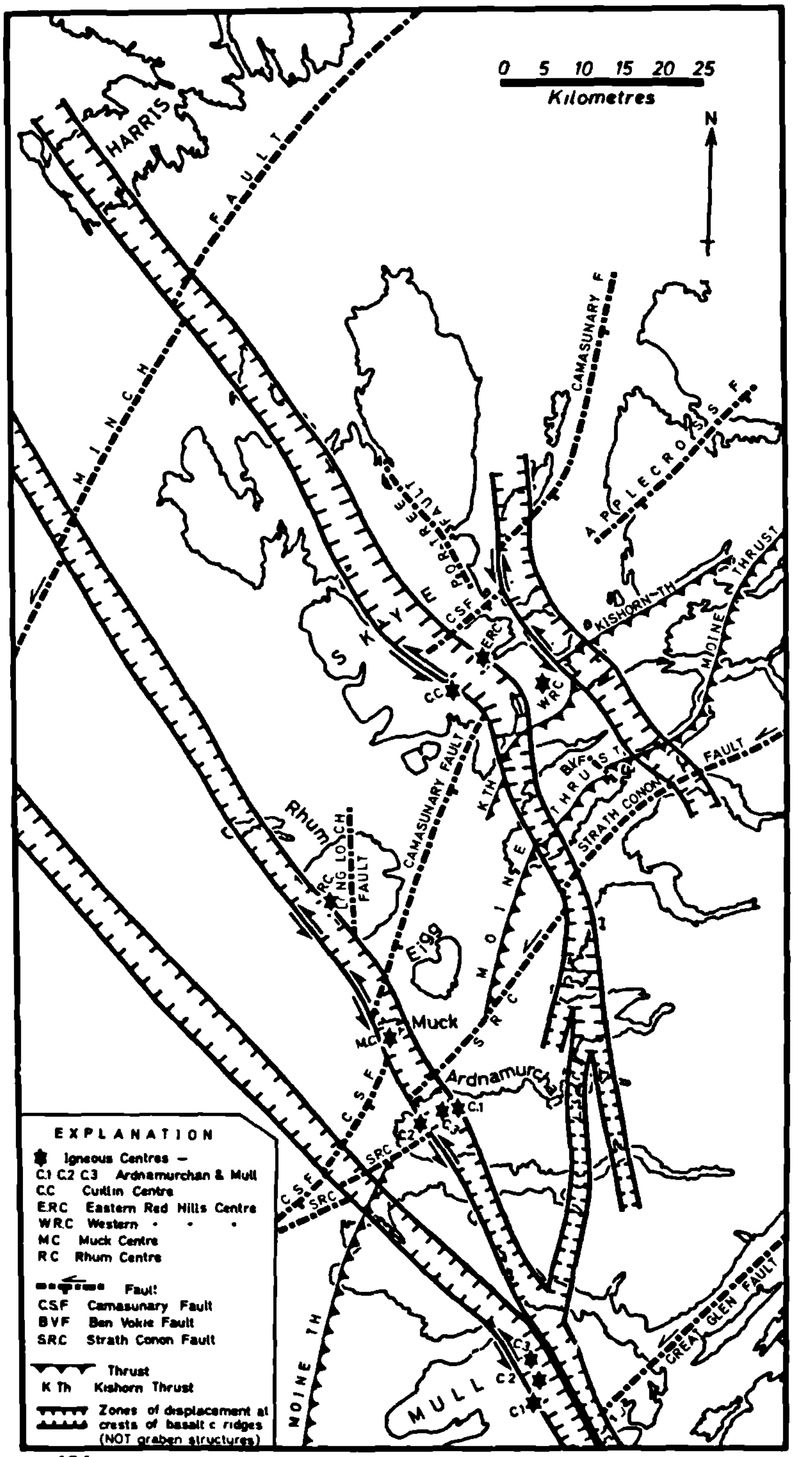


Fig 131. Sketch-map showing the intersections of the crests of basaltic ridges and zones of sinistral displacement with pre-Tertiary faults, in the Skye – Small Isles – Ardnamurchan – Mull districts (Positions of igneous centres in Mull after Skelhorn & Longland, 1969, p 15)

The axis of the Scalpay Secondary-Swarm shows no N.E. to S.W. displacement due to the supposed forceful intrusion of the Granite. This throws some doubt on Anderson and Dunham's opinion. Furthermore, McQuillin and Tuson (1965) gave evidence which suggests that the form of the Eastern Red Hills mass is a thin (less than 1km.) sheet, and as a consequence its emplacement involves only a small space problem. A displacement of the Camasunary Fault along a zone of sinistral strike-slip faulting (fig.131), which lies parallel to the dilation-axis of the Scalpay Secondary-Swarm, would involve no N.E. to S.W. lateral displacement of this swarm.

It is suggested that this displacement of the Camasunary Fault is evidence at the present surface of the greater transcurrent movements at depth. Some reasons why displacements along other zones depicted in fig.131 are not observed are: (i.) a cover of younger Tertiary lavas or sea obscures the evidence, and (ii.) the transcurrent movements are of greatest development at depth and decrease in magnitude to zero in some instances at the present surface.

Indications of N.N.W. transverse movements of Tertiary age are: (i.) along the Portree Fault (Anderson & Dunham, 1966,pp.175-6), which may pass from a normal to a transcurrent fault (though the arguments of these authors for its transverse character are based upon their interpretation of the form of the Eastern Red Hills bodies), and (ii.) along the Ben Vokie Fault in Sleat (Clough in: Peach et al.,1910, pp.149-50; Anderson & Dunham,1966,p.175).

(2.) Other pre-Tertiary Faults. Earlier, Richey (1937,p.32) had noted that the Central Complexes of Mull and Arran are at the sites where the supposed N. to S. zone of weakness joining the Tertiary plutonic centres intersects the Great Glen Fault and the Highland Boundary Fault, respectively. In the present context, however, the intersections of the Tertiary sinistral N.W. transcurrent displacements with the older faults are more significant.

The sites of the Tertiary Central Complexes on the ridge-system are at the points of intersection and displacement of the Camasunary Fault for Skye and the Muck proposed centre, and the Strath Conon Fault for Ardnamurchan. George (1966,p.6) proposed that the Camasunary Fault may pass between Coll (where only Lewisian rocks now remain) and Ardnamurchan (where middle Jurassic rocks outcrop): hence the siting of the Muck proposed central pluton. It is notable, too, that if the Applecross Fault were extended south-westwards (fig.131) it would intersect the magma-ridge underlying the Scalpay Secondary-Swarm at the region of greatest intensity of that swarm.

Where the Strath Conon Fault is intersected by the magma-ridge underlying the main regional linear-swarm of Skye, i.e. in the Sound of Sleat, the ridge is deeply located and has gentle slopes. Hence at this point a basaltic cylinder was not formed at high levels, but a "local high" of dilation and a bifurcation of the main dilation-axis at the present level of erosion may indicate a small cylinder of magma at deep level. Where the ridge underlying the Scalpay Secondary-Swarm meets the Strath Conon Fault probably no cylindrical magma body was developed at all, because of the great depth and weakness of the magma-ridge at this point.

Bailey (1944) concluded that the banding in the peridotites of the Central Complex in Rhum illustrates an asymmetry in the form of a N. to S. synformal axis near the Long Loch. Parallel to this fold-axis is the Long Loch Fault (figs.107 & 131). The fault is Tertiary in age and probably represents a zone of weakness initiated early in the intrusive period (Wager & Brown,1968,p.282), although it could well be the site of an earlier N. to S. line of weakness. Dunham (1970,p.30), on the other hand, preferred to think of the Rhum Central Complex as located on or near the Camasunary Fault. But whatever the nature of the line of weakness the intersection of a magma-ridge with it gave rise to conditions favourable to the uprise of a basic cylindrical magma body.

The Central Intrusive Complex of Mull is somewhat exceptional in that it is not obviously at the intersection of a ridge with the Great Glen Fault (fig.131). However, a cylinder of magma may have risen up one side (north side) of the fault only. The fault might in any case dip steeply north-westwards to meet the base of the cylinder at depth.

(3.) Lavas of Skye. A group of younger lavas in northern Skye are mostly confined to a N.W.-elongated central belt at the position of the main dilation-axis. A group of Tertiary faults, e.g. the so-called Greshornish Faults of Anderson and Dunham (1966,p.176), have produced a downthrown block and thus better preserved from erosion the younger lavas in this central belt. Such faults as these (illustrated in Sheet 80 and parts of 81, 90 and 91, Geological Survey, Scotland) are related to the collapse of the lava-pile of northern Skye into a basin-form elongated in the N.W. to S.E. direction. Such collapse is due to the shrinkage of the underlying magma-ridge during its consolidation, as well as due simply to the increasing weight of the lava-pile during its accretion.

(4.) Dip and Composition of Dykes. It is not supposed that the movements along the transcurrent fracture-zones were either of one discrete age or uniform and continuous. Rather it is suggested that these movements were spasmodic, and at each a differentiate was abstracted from the magma-source to produce the dykes and the lavas, as well as bodies of the Central Complexes. These numerous spasmodic movements help to explain why the dips of the dykes are generally so variable. It is also possible that at some stages the Lewisian basement rocks were melted by spasmodic super-activity near the magma-source (Ch.3:IVb.), and acid dykes were injected as a result, related to the emplacement of the Red Hills bodies. A source of acid magma also by partial melting of Lewisian rocks has been proposed for the Central Complex of Rhum (Dunham & Emeleus,1965; Dunham,1967), and by partial melting of silica-rich aluminous country-rock in the Carlingford Complex (Le Bas,1965).

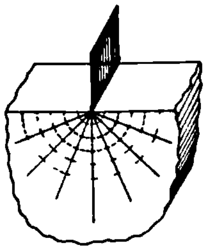
(5.) Termination of Skye-Swarm. The supposed termination of the ridge-system at depth at the line of the Great Glen Fault is intended to coincide with the corresponding termination of the Skye Dyke-Swarm. The ridge is not only at great depth at this locality but is also of very gentle inclination.

(6.) Off-set Dilation-Axes. The off-set of the dilation-axis to the north and south of the Central Complex of Skye (Axes 1 & 2, fig.48) is thought to be caused by a swing in trend of the crest of the magma-ridge beneath this region (fig.131).

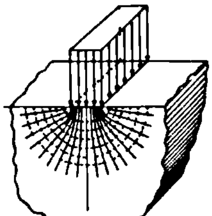
(7.) Topographic Features. The line of a N.N.W. to S.S.E. magma-ridge passes along western Rhum, through the Central Complex of Ardnamurchan, and along the northern part of the Sound of Mull (fig.131). The line of weakness which glaciers etched out as the Sound of Mull is in part attributed to a sinistral displacement at depth near the crest of an underlying ridge of basaltic magma, and to the collapse of that ridge during its consolidation. The separation by straits of sea of Raasay and Scalpay from Skye and the configuration of these islands are also of similar significance.

(8.) Mechanical Experiments. The crack patterns produced in metal plates or brittle coatings, under the influence of stress (Durelli et al.,1958), have their analogues in the dykes of the regional linear-swarms (fig.132).

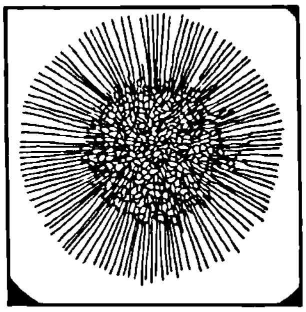
The analogue for the theoretical and experimental patterns shown in fig.132 a.,b.,c.,&d., is the array of dyke-fissures produced at the crest of the rising ridge of magma impinging on upper crustal layers. Each of the diagrams a. to d. can be viewed as an inverted section through the earth's crust, with the point of application of the load corresponding to a sharp (a. & b.) or obtuse (c. & d.) ridge of magma. In the highest crustal layers the dykes pass into sills (d.), as they are indeed found to do (Ch.10:II). The dykes of steepest inclination overlie the axis of the magma-ridge, and the dips decrease laterally away from the axis. However, it cannot be demonstrated in the Area of Study that the dip of the dykes is confocal to the crest of the ridge as are the cracks in the metal plates. As indicated earlier (Ch.10: II) the dip of any dyke is controlled by such a variety of



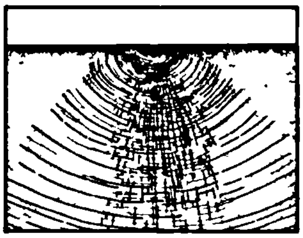
(a.) Stress distribution in a semi-infinite plate subject- to a concentrated normal load.



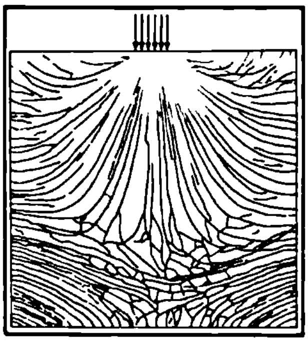
(c.) Stress distribution in a semi-infinite plate subject- ed to a uniform normal load on the edge.



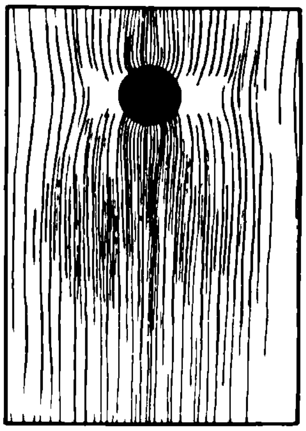
(e.) Crack pattern of an aluminium circular plate with clamped edges load- ed perpendicular to the plate with a uniformly dis -tributed pressure.



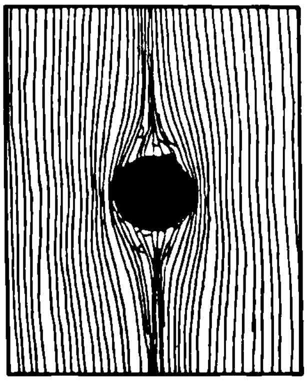
(b.) Stress distribution in a rectangular plate sub- jected to a concentrated normal load.



(d.) Stress distribution in a square plate subjected to a uniform normal load on the edge.



(g.) Crack pattern on one side of a plate with a hole, produced by direct loading.



(f.) Crack pattern pro- duced by relaxation load- ing with refrigeration.

Fig.132. Crack Patterns in Metal Plates Subjected to Stress. (Figs. a. to g. taken from Durelli et al., 1958, pp. 219, 220, 227, 228, 369, 436, 434)

factors that a regular pattern is not to be expected (also, Section 4, above).

A radial dyke-swarm might only be formed under rather exceptional circumstances, i.e. a rigid earth's crust subjected, not to the concentrated pressure near the crest of a whale-back ridge, but to a uniform force applied to a horizontal layer in the crust (fig.132e.).

The significance of the crack patterns in fig.132f. and g. is doubtful. In each case a plate with a circular hole was subjected to intermittent tension parallel to the length of the plate. In one case (fig.132f.) the brittle coat was cured after, and in the other case before (fig. 132g.), applying the tensile stress. Cooling (or refrigeration) was applied to facilitate opening of the cracks in the brittle coat. The pattern of cracks is roughly that of a regional linear dyke-swarm, with the hole acting as the site of the Central Complex. The tensile stress in the plate has its not too substantial analogue in the sinistral wrench-faulting in the earth's crust, parallel to which developed the dilation-axes of the dyke-swarms.

Fig.133 illustrates the locations of the crests of deep-seated basaltic ridges in the whole of the Hebridean region. Certain facts additional to those above (a. & b., below) seem to affirm the existence of the magma-ridges.

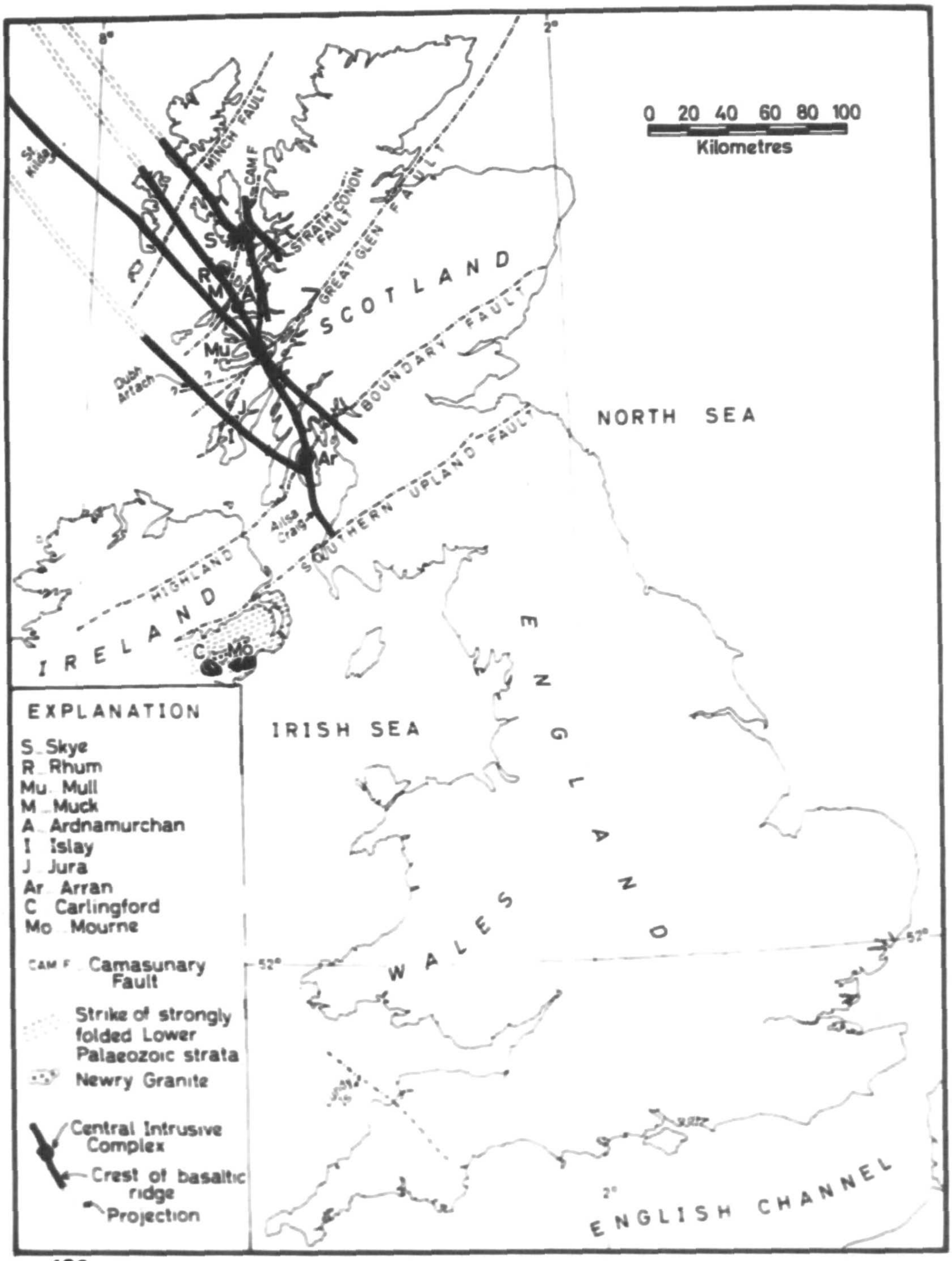


Fig.133. Sketch-map showing the intersections of the crests of basaltic ridges with pre-Tertiary faults Britain and Ireland (Geology taken from Tectonic map of Great Britain and Northern Ireland, first ed. 1966. I G S)

(a.) The locations of the Tertiary Central Intrusive Complexes are at points of crustal weakness where the sinistral transcurrent displacements and associated magma-ridges intersect pre-existing major faults, roughly at right-angles. In the Mourne-Carlingford district the Newry Granite, as well as the nearby Southern Uplands Fault, may have constituted a source of Tertiary crustal weakness. The Lundy dyke-swarm is somewhat anomalous. Cornwell (1970, p.288) considered that N.W.-elongated negative magnetic anomalies near Lundy are due to a 30km. dyke or dyke-swarm, constituting an extension of the Sticklepath Fault. The Sticklepath-Lustleigh fault-system suffered wrench movements in Tertiary times (Dearman,1963,p.281; Shearman,1967, p.556; Cornwell,1970,p.288; Owen,1971,p.292). Parallel and coincident to in this case the more characteristically dextral displacement a magma-ridge may again have developed.

The intersection of a magma-ridge with the possible extension westwards of the Great Glen Fault (Ahmad,1967), near Dubh Artach (fig.133), locates the site of the postulated central plutonic complex with which is associated the Islay-Jura Dyke-Swarm (Ch.13:III). According to Riddihough and Young (1970), however, the westward extension of the Great Glen Fault passes somewhat farther to the south, thus intersecting the magma-ridge at a point mid-way between Islay and Dubh Artach (fig.133).

(b.) Certain evidence is afforded by one additional feature of the present-day topography. It is supposed that the orientation of the mouth of Loch Fyne (to the north of Arran) is parallel to an underlying zone of transcurrent fracture in the crust and associated basaltic ridge. In these districts near northern Arran and Loch Fyne, a group of dykes of N. to S. trend are found (first noted by Clough in: Gunn et al., 1897), and these too are parallel to the proposed underlying ridge-system.

16:VII. Composition of Basaltic Ridges and their Source.

Holmes and Harwood (1929,p.43) suggested that the magma chamber underlying the Tertiary tholeiitic dykes of north-eastern England was possibly stratified, varying in composition longitudinally, transversely, and in depth. Reynolds (1931) envisaged a process of differentiation in a basaltic substratum to account for the order of intrusion of the various petrographic types among the Caledonian dykes of the Ards Peninsula (Northern Ireland). An elongate, updomed magma chamber, compositionally stratified by processes of differentiation, was suggested by Baker (1968) to explain the symmetrical geographic distribution of chemical variations in the alkaline parasitic bodies and dykes of Saint Helena. To account for the variety of compositions among the Tertiary dykes in the Area of Study, similar processes of stratification and differentiation (Ch.14:VI), and also assimilation, must be visualised.

According to Yoder and Tilley (1962) and Kushiro and Kuno (1963), following partial melting of ultrabasic material at different depths in the mantle processes of de-emulsification might yield various basaltic fractions: alkali olivine basalt from greater depths and tholeiite from shallower levels. The emulsion, which may consist of solid garnet-peridotite and liquid basalt, and later after de-emulsification the basaltic fraction, may both be impelled to rise under the influence of rising convection currents. Regardless of this, the slight decrease in density of the emulsion consequent upon partial melting of mantle material, and the very much lower density of the separated basaltic fraction, could be initially responsible for this uprise (Beloussov,1971,pp.59-61). The uprise reaches its most rapid rate if it takes place along fractures, such fractures acting as channels of reduced confining pressures (Beloussov, 1971,p.59). Beloussov argued that the uprise of the basaltic asthenolith is normally slowed down as the earth's crust is met with, since the density difference between the liquid basalt and crustal rocks is small and the buoyancy of the basalt is correspondingly reduced. He added, however, that the uprise of the basalt fraction may continue under its own inertia into crustal layers if a fracture zone can be utilized.

In the Area of Study, then, the proposed N.W. sinistral transcurrent faults predated the rise of the basaltic ridges. The uprise of the magma was facilitated to such an extent by these faults that surface lava-flows and numerous dyke-injections were possible. At the points of extreme crustal weakness, where the transcurrent faults intersected the planes of old faults, uprise of the magma was so expedited that a cylinder of magma eventually reached high crustal levels to form a central basic pluton (Skelhorn et al.,1971).

Spasmodic movements on the transcurrent faults and repeated collapses of the successively developed consolidated shells of the higher levels of the ridge and cylinder may have interrupted an otherwise quiescent process of differentiation in the basalt magma. Turbulence and quiescence would give rise respectively to alkali olivine-basalts alternating with the various compositions of dyke-sets and allied lava-groups, and finally ending with a surge of alkali olivine-basalt in the form of dykes during the final collapse of the magma-ridge (Ch.2:II; 14:IV). Stratification of the magma-ridge may also have been a result of uprise of basalt fractions derived by de-emulsification at different levels in the mantle. Cognate xenoliths incorporated in the dykes may have been derived from consolidated portions of the basaltic ridges and acid magmas at depth, as well as from the mantle.

The acid magma of the Red Hills bodies and associated dykes may have been derived by melting of basement material, especially near the central basaltic cylinder which possessed sufficient heat for this process. Indeed, Moorbath and Welke (1968A) deduced from lead-isotope studies of Tertiary ultrabasic, basic, and acid rocks from Skye that in all of these rock-types assimilation of crustal lead had taken place. In general the acid rocks were found to have more crustal lead than the basic and ultrabasic ones. The conclusion drawn by Moorbath and Welke was that the acid rocks may have been derived by partial melting of crustal rocks, with a smaller amount of acid material arising out of differentiation of the large basaltic bodies underlying the Red Hills.

16:VIII. The Rôle of the Central Intrusive Complexes.

Evans (1925,p.xcvii) was of the opinion that the convergence of the dykes of a regional swarm to a nodal region was due to the fact that the Central Complex lies at a point of weakness in the crust. Evans argued that the result was that dyke-fractures passed through the point of weakness, since less force was required than for them to continue at right-angles to the general tension. Even earlier Geikie (1897B,Ch.XL) had expressed a similar opinion.

To judge from the crack patterns in metal plates with holes (fig.132 f.&g.) it would seem that Evans was correct. On the evidence in Skye of the lower intensities of dykes in the Cuillin Gabbro than in the adjoining traverses (Ch. 7:VI), the continually rising central basaltic cylinder must have been liquid during most of the Tertiary igneous cycle. As a liquid, the basaltic cylinder was incapable of sustaining tensile or shearing stresses, and as such could act as a point of weakness. However, "synplutonic dykes" (Roddick & Armstrong,1959), i.e. dykes intruded into a liquid magma, may have developed, although the present author has not obtained evidence of this.

It is important to recognise that the Central Intrusive Complexes do not act as the fundamental focus of the regional linear-swarms. Rather the point of weakness, at which the cylindrical magma body rose and towards which the dyke-swarms increase in intensity, is the fundamental factor.

In the context of the present author's postulated mechanism of origin of the British Tertiary Dyke-Swarms the rôle of the Central Complexes as initiators of dyke-injection is diminished. Possibly a few dykes of limited geographical extent were flushed out laterally from the cooling and perhaps contracting cylindrical basaltic magma body (Ch. 10:II&III), e.g. the ultrabasic dykes of the Cuillins and Strathaird focussing on the Sgùrr Dubh mass (Gibb,1968,pp.

434-5). However, lateral flow over great distances seems improbable (Ch.15:II,ii).

The most significant rôle of the central magma cylinder is in the melting of crustal material to yield acid magmas. Examples of the restriction of acid dykes to the neighbourhood of Central Complexes are not confined to Tertiary volcanic districts. The acidic members of the so-called radial-dykes (Clough,1888,p.28), located nearer the Cheviot Hills Granite focus than the basic varieties, may have a similar origin through melting by an underlying cylinder of basic magma of crustal rocks, and not entirely by a process of differentiation as proposed by Kynaston (1899, p.413). In addition, the higher temperatures in the crust in the vicinity of the basic magma cylinder would not only have led to proportionately greater melting of the crust there than elsewhere, but also under these higher temperatures reduction in the viscosity of the acid magma so produced would have enhanced its injection to higher levels.

In the Area of Study dyke-fissures could obviously act as forerunners of each stage of the continuous uprise of the magma-ridges and magma-cylinders. During the earlier stages the dyke-sets and allied lavas would bear no apparent relationship to the then deep-seated magma-cylinder which rose to form the Cuillin centre (Ch.14:VI). The configuration of the dyke-swarm, however, would become progressively more symmetrical about the presently located dilation-axes, and confocal about the point of weakness at the site of the Cuillins as the underlying reservoir reached higher levels.

16:IX. Ocean-Floor Spreading in the Atlantic.

There still remains to be explained the ultimate cause of the postulated transcurrent faults underlying the dilation-axes and the tensional forces at right-angles. It is thought that the explanation of these lies in an understanding of the evolution of the Atlantic Ocean.

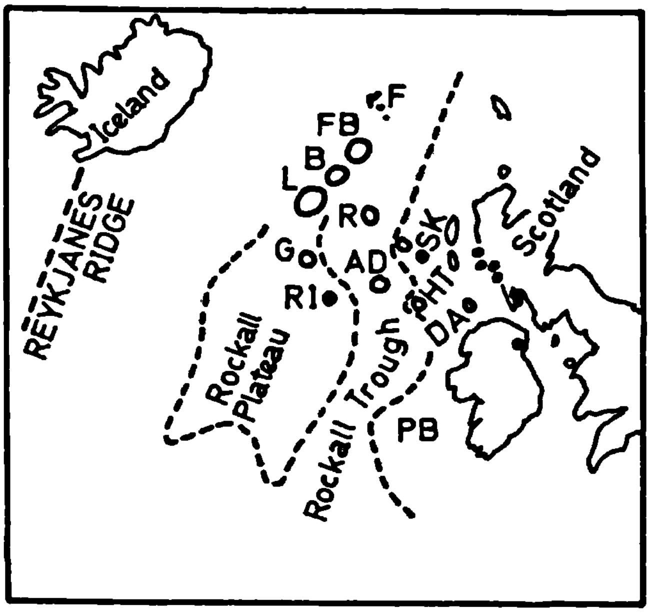
Ocean-floor spreading, first suggested by Hess(1962), elaborated by Vine and Matthews (1963), and corroborated by Heirtzler and others (1966), is now recognized in all principal ocean basins (Heirtzler et al.,1968). In the Atlantic Ocean, the new ocean crust, generated at the Mid-Atlantic Ridge, and the adjacent continents are both assumed to have behaved as rigid plates in the manner suggested for the North Pacific (McKenzie & Parker,1967).

Bullard and others (1965) recognized four poles of rotation in the Atlantic Ocean, about which four join-segments separated in pairs at the Mid-Atlantic Ridge: (i) South America and Africa, (ii.) Africa and North America, (iii.) North America and Europe, (iv.) Europe and Greenland. On the basis of available palaeontological and magnetic survey data, Funnell and Smith (1968) proposed a time-scale for the separation of the first three of these pairs, each beginning at 200 m.y. B.P. The separation of Greenland and Europe began at 65 m.y. B.P. (Bullard et al.,1965).

The rôle played by the Rockall Plateau in the breakup of the north-east Atlantic is significant. A review of the seismic refraction data (M.N. Hill,1952; Gaskell et al., 1958; Ewing & Ewing,1958) indicates that the crust west of the Rockall Plateau is oceanic, i.e. formed by sea-floor spreading. To the east of the Rockall Bank, i.e. in the Rockall Trough, the crust, below a thick sequence of sediments, is of problematic origin (Roberts,1970). The western margin of the Rockall Plateau lies parallel to the Reykjanes Ridge axis. To achieve the best fit reconstruction of the North Atlantic continents (i.e. before spreading), Bullard and others (1965) suggested that the Rockall Plateau is continental in origin and composition. In fig.134b. the Rockall Plateau has been rotated from its present position (fig. 134a.) and conjugated with the Scottish continental margin. Additional corroboration of the continental nature of Rockall Plateau comes from Rockall Island which is composed of aegirine granite (Sabine,1960,1965; Miller & Mohr,1965) derived by partial melting of rocks of continental composition (Moorbath & Welke,1968).

Moreover, a circular +120 mgal. gravity high and high amplitude magnetic anomalies (Roberts,1969) just east of Rockall Island are thought (Roberts,1970) to be associated

(a.)



EXPLANATION : ...Topographic trends. ● ...Tertiary Central
o ... Intrusive Complex / Seamount-Tertiary? C Intrusive Complex.
F...Faröes. FB... Faröe Bank. B... Bill Bailey's Bank. L...Lousy Bank.

SK... St. Kilda.
HT... Hebrides Terrace.
DA... Dubh Artach.
PB... Porcupine Bank.

G... George Bligh Bank.
RI... Rockall Island.
R... Rosemary Bank.
AD... Anton Dohrn.

(b.)

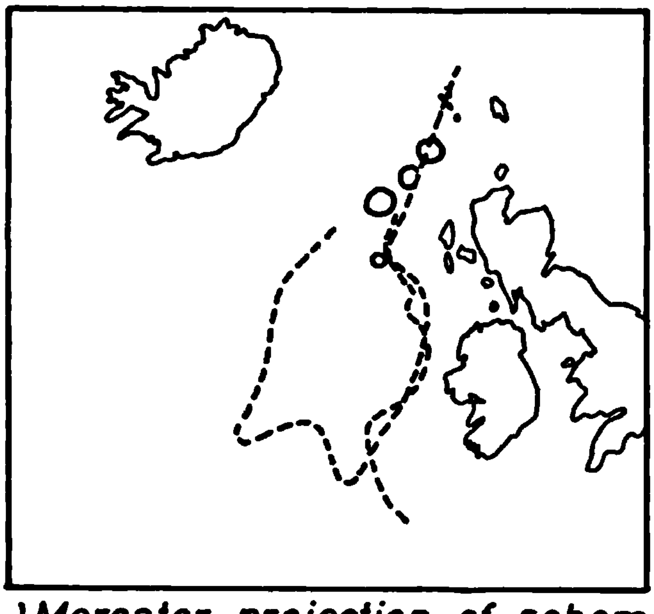


Fig.134. (a.) Mercator projection of schematic bathymetry of the present N.E. Atlantic about the pole of rotation (Bullard et al., 1965), at 73°N., 96·5°E. (b.) Rockall Plateau rotated and conjugated with the Scottish continental margin. (After Roberts, 1970, p.91)

with a large Tertiary igneous centre. Similar circular gravity highs, each perhaps indicative of basic complexes intrusive into continental crust, are recognized at: (i.) Anton -Dohrn (+169 mgal.); (ii.) the Hebrides Terrace (+128 mgal.); (iii.) about 40km. north-west of St. Kilda (+160 mgal.); and (iv.) to the north-west of Islay (+130 mgal.), i.e. the possible focus of the Islay-Jura Dyke-Swarm near Dubh Artach (Ch.13:III). The first of these localities is within the area described as the Rockall Trough (fig.134a.).

In the ocean basin west of Rockall Plateau, three spreading episodes have been recognized (Avery et al.,1969). The earliest spreading (65 to 50 m.y. B.P.) was from a ridge trending N. 40 deg. E.; between 50 m.y. and 15 m.y. B.P. E. to W. spreading took place about a N. to S. trending ridge axis; the latest spreading (10 to 15 m.y. B.P.) occurred at the N.E. to S.W. trending Reykjanes Ridge axis.

16:X. <u>The Tectonic Results of Ocean-Floor Spreading at the Labrador-Biscay Rift.</u>

Long before the three recognized spreading episodes in the ocean basin west of Rockall Plateau, a major separation of crustal plates in the North Atlantic was effected at the Labrador-Biscay rift, where the North American and European join-segments divided. Since (i.) the situation developed during the Labrador-Biscay rifting is in many ways analogous to that developed during the later Greenland/Europe rifting, and (ii.) the tectonic relationship between the North America/Europe and Greenland/Europe join-segments is of some significance to the evolution of the British Tertiary dyke-swarms, then a description of the Labrador-Biscay rift is profitably interposed at this stage.

Using J.T. Wilson's (1962,1965) concept of transform faults, Webb (1968) interpreted the sinistral movement of the Great Glen Fault and the dextral movement of its counterpart the Cabot Fault in Newfoundland as results of the Labrador-Biscay rifting. Russell and Burgess (1969), taking their cue from Gass and Gibson (1969) and from the geophysical studies of Sheridan and Drake (1968), suggested a Devonian-Carboniferous age for the rifting, which is notably somewhat earlier than that proposed by Funnell and Smith (1968). The North American and European join-segments moved apart in opposite directions, west and east.

Russell (1968) and Russell and Burgess (1969) concluded that N. to S. geofractures and faults in Ireland (fig.135), separated by distances of 50 to 60km., were developed as the result of an E. to W. tension related to the rifting, and could be regarded as jointing on a large-scale in a brittle earth's crust. Such geofractures are characterized by faults, monoclines, and large base metal deposits. A similar geofracture in England, taken by Russell and Burgess (1969) from the "Tectonic Map of Great Britain and

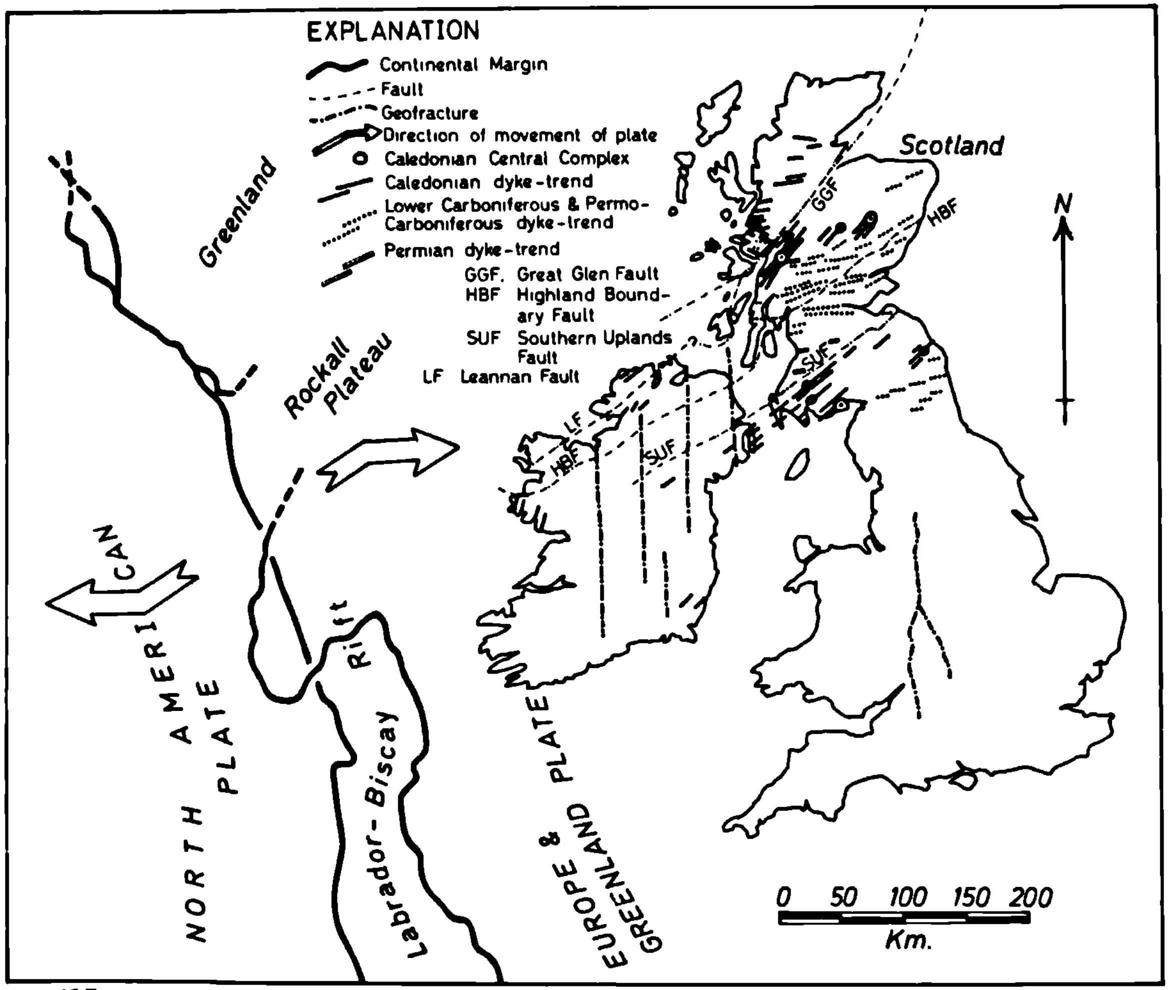


Fig.135. Results of the Labrador-Biscay rift. [Dyke-swarm trends after Richey, 1939, pp. 403, 413, 417; westward extension of Leannan Fault after Crow et al., 1971, p. 582; other data after Bullard et al., 1965, Webb, 1968, Russell, 1968, Russell & Burgess, 1969, and from the "Tectonic map of Great Britain and Northern Ireland" (1966).]

Northern Ireland" (1966), was also cited (fig.135). By analogy with the joint model proposed by Price (1966), Russell and Burgess deduced that such a regular spacing at 50 to 60km. is to be expected, and noted that a similar spacing of geofractures has been observed in Czechoslovakia (Kutina et al.,1967). Recently Russell (1972) has suggested that three N. to S. geofractures of late-Carboniferous age, and again spaced at about 50km. separation, are located at the base of the upper crust in Scotland. These are the Loch Lomond, Alva-Thornhill and Buckhaven-Innerleithen geofractures.

Russell and Burgess (1969) suggested that during rifting it is probable that high positive pore pressures may develop in the crustal rocks due to mantle degassing, and as a result tensile failure characterizes the geofractures. They added that some E. to W. dextral shears in Ireland, noted by Charlesworth (1963) and Rhoden (1958) could then be easily understood in terms of differential movement of the continental margin away from the Labrador-Biscay rift. Formerly these shears had been regarded as the consequence of Hercynian orogeny. Russell and Burgess went on to say that Westoll (1965) had "pointed out that the Carboniferous basalts in the British Isles may be related to continental drift" (Russell & Burgess,1969,p.1056). Such lavas are related to centres which often occurred along N.E. to S.W.

Caledonian lines of weakness. These lines of weakness, in Scotland at least, have been shown to be numerous (Auden, 1954; MacGregor, 1967; also fig.124). The later dyke-swarms have an E. to W. trend (fig.135) and "may have arisen from shears at the base of the lithosphere caused by differential movement away from the rift" (Russell & Burgess, 1969, p.1056).

Auden (1954) recognized three sets of Caledonian fractures in Scotland. However, he described them as more or less synchronous. In a region comprising the counties of Argyll, Perth, Inverness, and most of Ross and Cromarty, the dominant feature is the N.E. to S.W. pattern of fractures, accompanied by E. to W. fractures in the centre of this region (fig.124; and Auden, 1954, p.343 for districts to the east not illustrated in fig.124). In the north of Scotland in Sutherland, Easter Ross and Cromarty, the fractures are mostly WN.W. to E.S.E.

The deductions made by Russell and Burgess (1969) appear to be consistent with the observed facts, and perhaps the fractures described by Auden are not exactly synchronous. Fig.135 illustrates some of the features described by Russell and Burgess, with information also on the trends of the dyke-swarms. The Caledonian (mainly Lower Old Red Sandstone) dykes of Scotland are undoubtedly mainly of N.E. to S.W. trend (Richey, 1939, p.403), paralleling the major faults (Great Glen and Southern Uplands Faults) and fractures, and perhaps paralleling an early direction of separation at the rift (fig.135). The E. to W. Caledonian dykes of northern Scotland (north of the Great Glen Fault) are possibly of somewhat later date and perhaps related to a westerly drift away from the Labrador-Biscay rift. The Lower Carboniferous dykes and some of the Permian dykes of Scotland (Richey,1939,pp.413,417) are of E. to W. trend and could be concomitant with E. to W. drifting. The chief anomaly arises out of the W.N.W. to E.S.E. trend of the Permian dykes extending from eastern Ardnamurchan towards Loch Linnhe (Appendix 26), although the axis of this swarm may constitute a later geofracture intersecting at right-angles the Great Glen Fault.

The Newry Granite (fig.133) appears to be located on a N. to S. geofracture near its intersection with the Southern Uplands Fault. The Strontian Granite (fig.4) might have developed on a fracture, prior to that sinistral movement on the Great Glen Fault which separated the Strontian from the Foyers Granites. Other major Caledonian plutons (Ben Nevis, Glen Etive, Glen Tilt, Lochnagar, Loch Doon, Cairnsmore of Fleet, Criffel, and Cheviot) are located not on major faults but again may conceivably be sited on N.E. to S.W. fracture zones.

16:XI. The Tectonic Results of Ocean-Floor Spreading in the North-East Atlantic.

The key to the origin of the dyke-swarms in the Area of Study lies in an understanding of the tectonic conditions obtaining at the time of their formation. It would be fruitless to make too detailed comparisons, for instance, between the Tertiary Hebridean volcanic districts located near the edge of a continent and the volcanic region of Iceland located in a purely oceanic environment. In Iceland crustal drift (amounting to 400km. since activity began), away from a central active volcanic zone astride the Mid-Atlantic Ridge, was and is the result of dyke-injection (Bodvarsson & Walker,1964). North-western Scotland, on the other hand, developed its volcanic bodies in the lithosphere at the very onset of rifting.

Webb (1968,p.878) suggested that the line of the Greenland/Europe rift was in some measure predetermined by the trend of the N.E. Caledonian faults of Scotland developed during the Labrador-Biscay rifting. The present author also proposes that these same faults adopted the rôle of geofractures during the N.N.W. to S.S.E. separation by rifting of the Greenland and Europe plates. Evidence for Late-Cretaceous or early Tertiary movement on one of these old faults, the Great Glen Fault, has been observed by the present author (Appendix 26). The Camasunary Fault is known at least to have suffered movement at a slightly earlier period (VI,1, above). And it is not unlikely that other older faults suffered some displacement during the same periods.

As a first hypothesis, differential movement of the continental margin away from the Greenland-Europe rift ("pivot" about pole of rotation, fig.138) may have given rise to the proposed Tertiary sinistral transcurrent displacements, arising at the base of but sometimes also intersecting the lithosphere.

Alternatively, adopting Webb's concepts for the Labrador-Biscay rifting, the proposed sinistral N.N.W. faults of the Hebridean and Irish region may have acted as transform faults at the north-eastern end of a zone of rifting between Rockall Plateau and Porcupine Bank. Once more differential movement between Rockall Plateau and Scotland/Ireland may have accentuated the development of these faults. In this, the second hypothesis, dextral faults must have developed at the south-western limit of the zone of separation. Indeed, dextral movement along faults is known to have occurred at this time in south-west England (e.g. Sticklepath-Lustleigh system). Moreover, a group of Tertiary Central Complexes would by this hypothesis have developed on the Rockall Plateau side of the rift, overlying dextral-slips near the northern end of the Plateau and sinistral-slips near the southern end. Unfortunately evidence of such transcurrent faults is as yet lacking for Rockall Plateau.

Nevertheless, this second hypothesis is preferred, even though it contradicts both Roberts' statement (1970,p.90) that the Rockall Trough zone of rifting is probably of Lower Mesozoic age, and Bott and Watts (1971,p.101) suggestion that "the Rockall Trough may have formed or been forming as a Red Sea type trough in Permo-Triassic time". It might be said that a Lower Mesozoic period of movement predated the Tertiary rifting, but the lack of development of dyke-swarms in the Lower Mesozoic to the same extent as the Tertiary dyke-swarms in Scotland indicates that this would have been of very much lesser intensity than the proposed Tertiary separation of Rockall Plateau from the British mainland. Roberts' own hypothesis was that the British Tertiary dyke-swarms are related to "the development of the fan shaped anomalies associated with the Iceland-Faröes Rise" (1970,p.90), although it is not clear exactly what he meant. His hypothesis seems unlikely chiefly because of the remoteness of the Rise from the line of the Hebridean, Irish, and especially Lundy dyke-swarms.

To make matters more complex a transverse fracture zone, of the type proposed by Funnell and Smith (1968), must have developed between Greenland and Spain (fig.137), due to the differential movement between the Greenland/Europe join-segments and the North America/Europe join-segments.

The Jan Mayen fracture zone may constitute a similar feature (fig.137). Again adopting Webb's (1968) ideas, the transverse fracture zone between Greenland and Spain must also have acted as a major transform fault.

Russell and Burgess (1969) have suggested that the E. to W. Permian and Permo-Carboniferous dykes of Scotland were emplaced parallel to transcurrent faults developed upon the separation at the Labrador-Biscay rift. For the Tertiary dyke-swarms of Britain the present author adds that not only the swarms, but also the associated basaltic ridges, developed parallel to the N.N.W.-trending wrenches.

Tertiary dykes are also found in Norway (Storetvedt, 1965). Fig.136 illustrates a possible magma-ridge underlying this W.N.W.-trending swarm. The location of the Norwegian swarm is such that it must be related to Greenland/Europe rifting, and not to the Rockall Plateau separation.

The dyke-swarm of Greenland, lying parallel to the line of the Greenland/Europe rift, and the Jurassic dyke-swarm of western Greenland, lying parallel to the Mesozoic (Watt, 1969) Greenland/Labrador rift (fig.136), both create problems in the context of the present author's ideas. These swarms can be likened to the dykes of mid-ocean ridges, lying parallel in both cases to the associated axis of rifting. There are certain similarities, however, between these Greenland swarms and the Tertiary dyke-swarms of north-

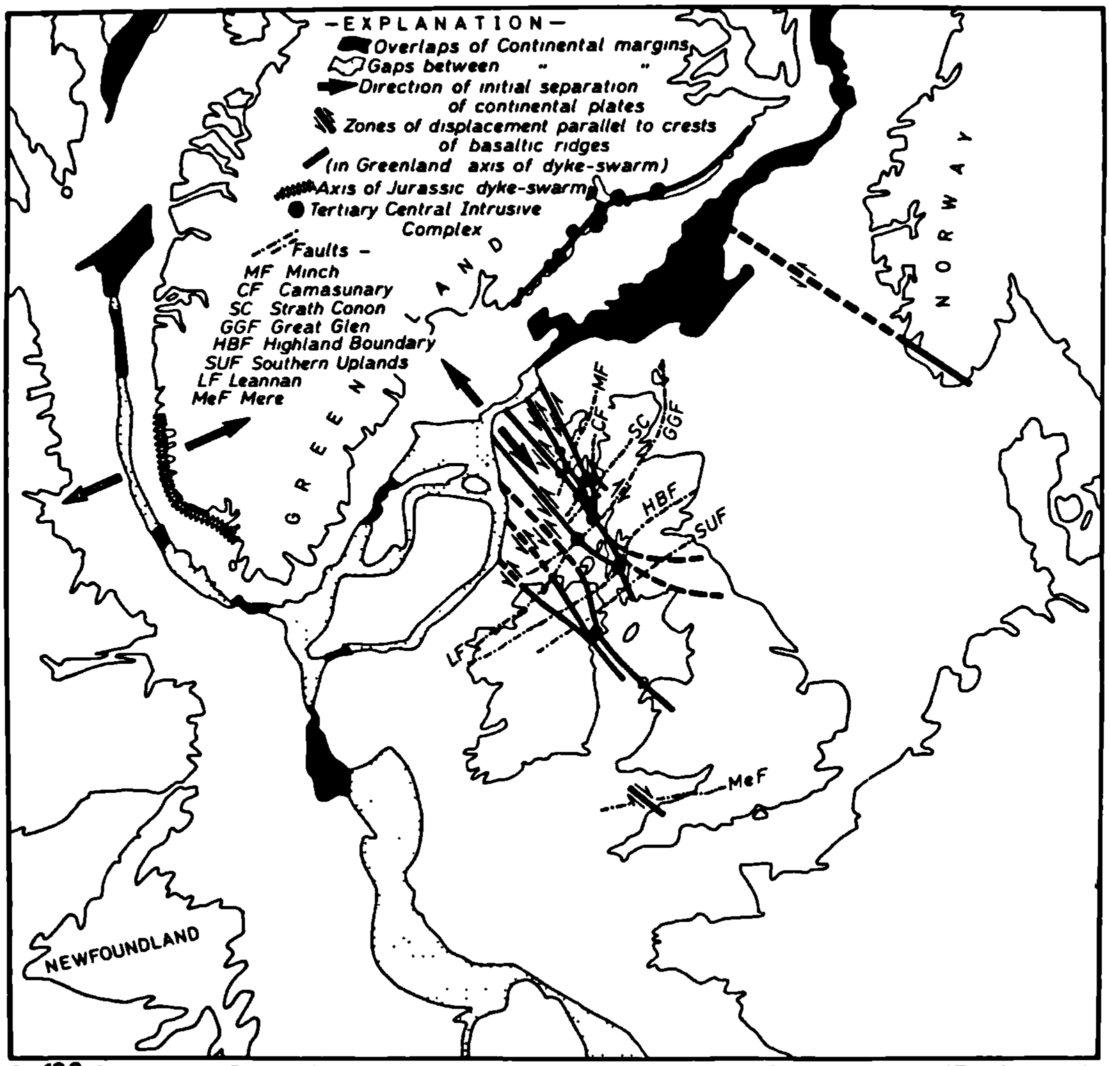
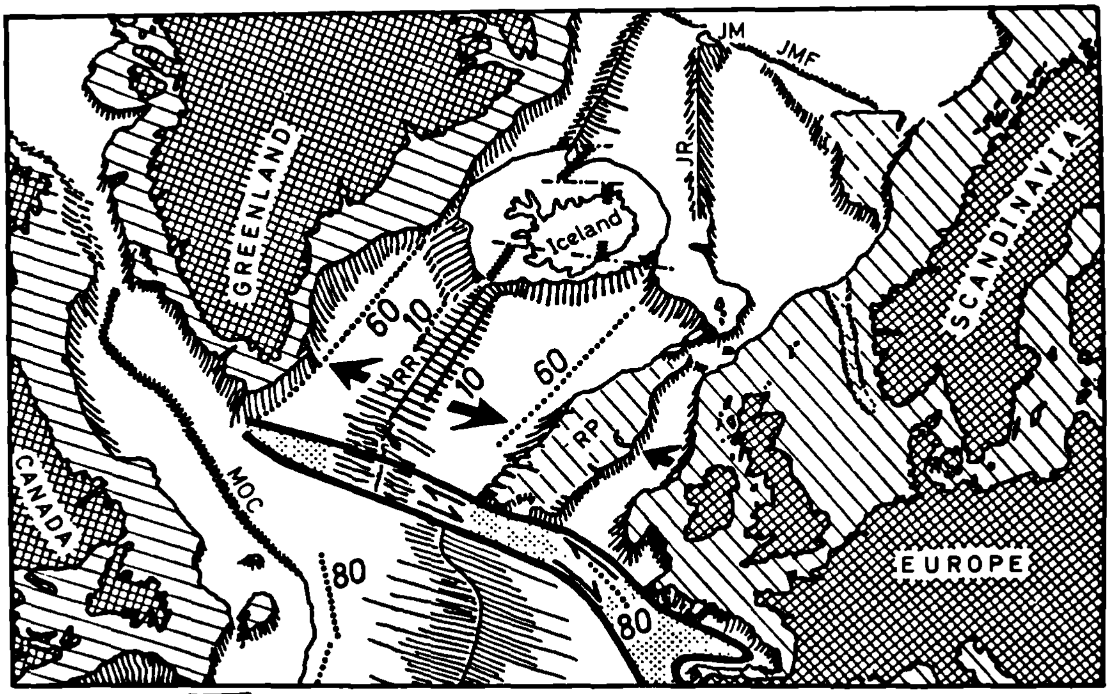


Fig 136. Results of the Europe-Greenland rift (and Labrador-Greenland rift). Conical projection. (Fit of the continents after Bullard et al.,1965, Jurassic dykes in SW Greenland taken from Watt, 1969, p 1321, approximate location of dykes of Norway after Storedvedt, 1965, Tertiary Central Complexes in E Greenland after Wager & Brown, 1968, p 13; Mere Fault after Owen, 1971, p 290)



EXPLANATION Transverse fracture zone. —·—·— Transverse fault.
Position of Mid-Atlantic Ridge in Iceland. ······ Isochrons (m.y.).
Direction of separation of continental masses in N.E. Atlantic.
JM .. Jan Mayen. JMF... Jan Mayen fracture zone. JR... Jan Mayen Ridge. RR... Reykjanes Ridge.
RP.. Rockall Plateau. MOC... Mid Ocean Canyon.

Fig. 137. Transverse Fracture Zone between Greenland-Europe join -segments and North America-Europe join-segments. (Mercator Projection.) [Topography of the North Atlantic Ocean floor after the "Atlantic Ocean Floor", National Geographic Society, 1968; isochrons and location of Mid-Atlantic Ridge in Iceland after Heirtzler, 1968, p.7]

western Scotland, most notable of which is the arrangement of the Central Complexes along lines roughly parallel to the line of the associated rift.

According to Menard (1969,p.128), at the onset of mid-ocean rifting, the source of the magma for the trailing edges of the separating plates is a pool in the low-density mantle. Menard believed that such a pool may at that time have also extended beneath the continental crust. Fig.138 illustrates just such a situation. Under the influence of rising convection currents the composition of this pool may have varied laterally. As long ago as 1950, Browne and Cooper had recognized that high positive gravity anomalies in the Porcupine Bank and Rockall Bank areas might be related to the past existence of an upward convection current (Ch.12:III).

Some confirmation of a lateral variation in the composition of the magma-pool (fig.138) comes from the model of mantle-convection and heat-flow in ocean ridges suggested by Oxburgh and Turcotte (1968) and later by Oxburgh (1971, p.283) alone. In this model tholeiitic magma is said to be generated in or near the axial zones of ridge-systems, with alkali basalt forming at greater depth on the flanks or outer margins of active volcanic zones (Gast,1968). The model is supported by the occurrence of late-Quaternary alkali basalts outside the main active belt of tholeiitic volca-

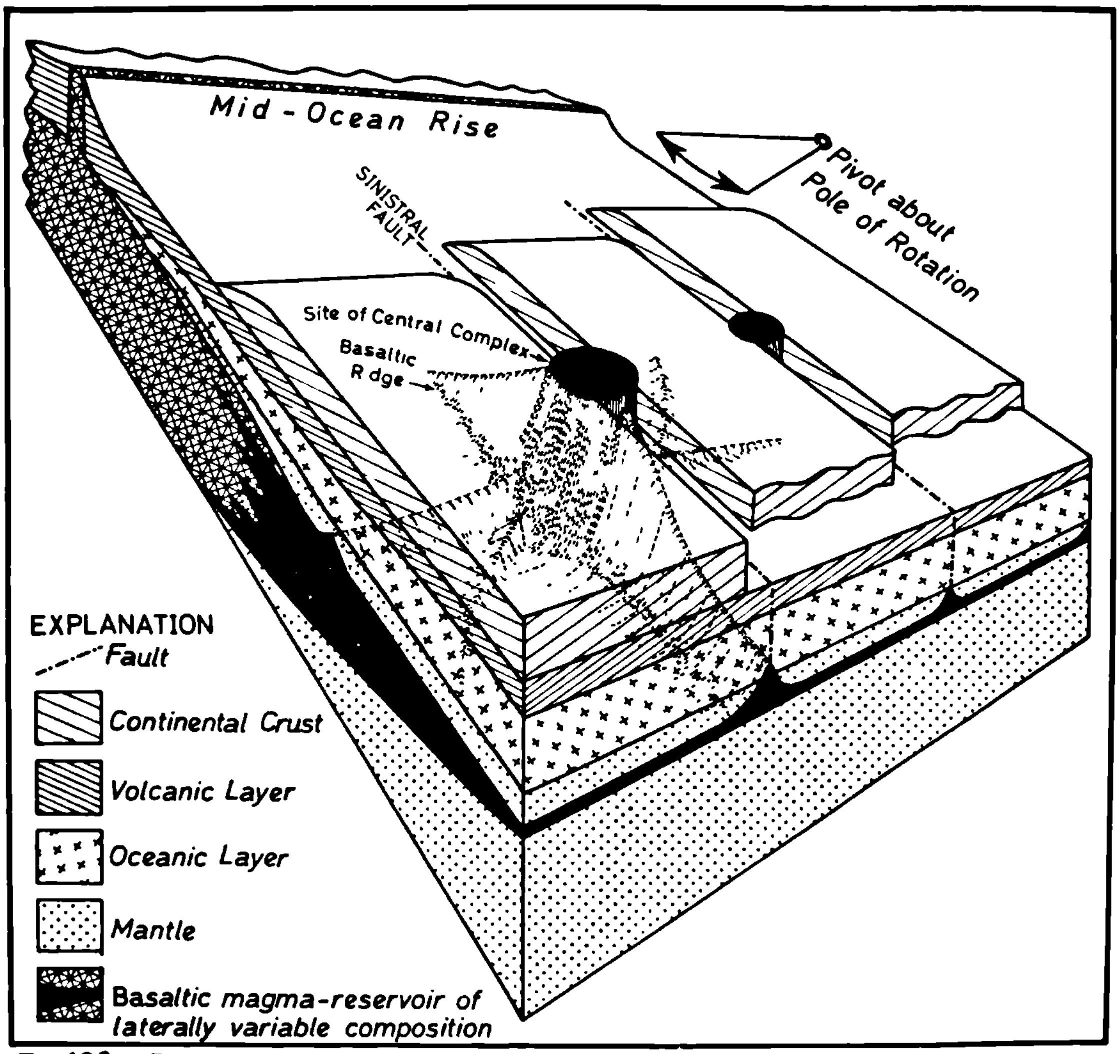


Fig.138. Block diagram to illustrate the development of zones of sinistral displace -ment. The relationship of the basaltic ridges to mid-ocean rifting.

nism in Iceland (Sigurdsson,1969). Moreover, the average $^{87}Sr/^{86}Sr$ value for Icelandic rocks (on the rise-ridge) is significantly different from that for the Tertiary basic rocks of Skye (on the continental margin) (Moorbath & Bell, 1965A).

The present author believes that during the onset of the Rockall Plateau/British mainland separation, the rising magma-ridges underlying the Tertiary dyke-swarms could tap both tholeiite and alkali basalt magmas. Later, normal processes of differentiation may have developed in the magma-ridges (Section VII, above).

It is possible that Richey (1939,p.32) was not mistaken in his opinion that the intersection of a N. to S. zone of weakness with the pre-Tertiary faults helped to locate certain of the Tertiary Central Complexes. Movement in Tertiary times on N. to S. fractures in Ardnamurchan, Moidart, Sunart, and Morvern, has been described (MacGregor,1967,p.10). In the present context it is possible to regard the N. to S. zone of weakness described by Richey, and said to extend perhaps southwards to Lundy (Dollar,1968,p.119), as an earlier-developed (Caledonian) geofracture. The Long Loch Fault may also have begun as a Caledonian geofracture in Rhum. Auden (1954,p.346) had also remarked that relief of stress in Tertiary times in places occurred along pre-existing (Caledonian) planes of weakness.

Rhodes (1971) demonstrated that the ages and the geographic arrangement (along lines) of ring-dyke complexes, which possibly developed over fixed plumes in the asthenosphere, could be used to indicate the direction of movement of plates away from a mid-ocean rift. The radiometric-dates of igneous bodies in Rockall, St. Kilda, Skye, Ardnamurchan, Mull, Arran, and Lundy, are all about the same (Ch.12:V). Moreover, an age of 52 m.y. has been determined for a specimen of the lavas of the Faröes (Tarling & Gale, 1968). The indications then are that the centres were developed almost simultaneously in two groups — (i.) Rockall Island, George Bligh Bank, Lousy Bank, Faröes Bank, Faröes, and (ii.) the centre near Dubh Artach (Blackstones), Hebrides Terrace, St. Kilda, the centre 40km. north-west of St. Kilda, and the centres of north-western Scotland, northern Ireland, and Lundy (fig.134). The similarity of ages of the two groups lying on either side of the Rockall Trough constitutes additional evidence of the Tertiary separation of Rockall Plateau.

The Mourne Granite and Antrim basalts are, nevertheless, conspicuously much older than the Tertiary volcanic rocks of Scotland. If the dates (Ch.12:V) on these Irish rocks are correct, then the indications are that the Rockall Plateau broke away from the British mainland first in the south, and subsequent separation was of pivotal type about a point to the north, perhaps at the Iceland-Faröes Rise. Such pivotal motion again would not only enhance the development of sinistral transcurrent faults (fig.138), but also tend to suppress the development of the complementary dextral-slips of transform type to the south. A paucity of dyke-swarms in south-west England was the result.

Differential movement of blocks of continental material in the manner illustrated in fig.138 would also lead to tensional stress being developed at right-angles to the direction of movement of these segments. Such tensional stress might lead to a separation of the blocks in an E.N.E. to W.S.W. direction (fig.138). In practice, however, discrete zones of separation did not develop but the rising basaltic ridges and dyke-swarms occupied the tension gashes as they developed.

A corollary of the proposed mechanism of origin of the Tertiary dyke-swarms of Britain is that N.E. to S.W. trending dyke-swarms most probably developed parallel to the line of separation of the Rockall Plateau and the British mainland. In this case, N.E.-trending dyke-swarms may be associated with the seamounts of questionably Tertiary age of Anton-Dohrn and Rosemary Bank (fig.134), lying in the Rockall Trough and presumably on the line of the rift.

16:XII. Summary of the Tectonic Background to the Origin of the British Tertiary Dyke-Swarms.

The Rockall Trough developed at the line of the Tertiary rifting between the Rockall Plateau and the British mainland. An earlier period of rifting, though of lesser degree, may have taken place along this same line in Lower Mesozoic times. During the Tertiary separation of the continental blocks of the Rockall Plateau and Britain, a series of spasmodically developing N.W. or N.N.W., transcurrent faults were formed at the base of the lithosphere but sometimes also intersecting higher levels. These faults were located at both ends of the zone of rifting. At the northern end, the transcurrent faults were of sinistral type on the eastern side of the rift (Scotland and Ireland), and of dextral type on the western side (northern part of the Rockall Plateau). At the southern end of the zone of rifting the transcurrent faults were of dextral type on the eastern continental segment (south-western England) and of sinistral type on the western segment (southern Rockall Plateau).

A transverse sinistral fracture zone between Britain and Spain, caused by differential movement between the Greenland/Europe join-segments and the North America/Europe join-segments may have accentuated the development of the N.W.-trending sinistral wrenches. Such a fracture zone may also have reduced the effectiveness of the dextral transcurrent faults in south-western England. Separation at the Rockall Trough rift about a pole of rotation to the north (probably located on the Iceland-Faröes Rise) would also create, by virtue of its pivotal nature, a reduction of the influence of dextral transcurrent movements in the continental segment to the south-eastern side of the Rockall Trough.

Ridges of basaltic magma, arising from the compositionally variable (in a lateral sense of direction) magma-chamber lying beneath the rift and also passing under the continental blocks on either side, ascended the N.W.-trending transcurrent faults. Where the transcurrent faults intersected pre-existing major N.E.-trending faults, which at this Tertiary period acted as geofractures, the uprise of the basaltic magma was accentuated and cylindrical bodies eventually reached the levels of the Tertiary basic plutons seen outcropping today.

As a result of the N.W. to S.E. separation of Rockall Plateau from Britain two synchronous series of Central Intrusive Complexes were produced, each along the edge of the respective continental block — Rockall Plateau and Britain. For the latter series, at least, it can be added that not only does it, like the former series, lie parallel to the Rockall Trough line of rifting, but also perhaps to an earlier N. to S. Caledonian geofracture.

The Tertiary dyke-swarms of Britain (and a corresponding series no doubt on the Rockall Plateau) developed parallel to the transcurrent faults and arose mainly from the basaltic magma-ridges, although a few dykes may have been related to the central basaltic cylinders. An important consequence of the N.W.-trending transcurrent faults was a differential movement of sections of the continental crust away from the line of the Rockall Trough rift. This differential movement produced virtual separation of these sections of crust in a N.E. to S.W. direction. The effect of this was to create relative N.E. to S.W. tension which was relieved, not by separation of each adjacent pair of crustal sections at a discrete line, but by the emplacement of a magma-ridge at depth and a dyke-swarm, whose major axis followed the line of the associated N.W.-trending transcurrent fault, at higher crustal levels.

Chapter Seventeen

FUTURE RESEARCH ON THE DYKE-SWARMS

17:I. Introduction.

Lack of time and equipment precluded the pursuance of investigations along a number of courses. Opportunities for future study are considered under nine heads. The first seven of these deal with possible future researches into those swarms described in this thesis:-

(i.) Statistical analyses of a more complex type of the purely numerical data, e.g. on trend, dip and thickness of the dykes.

(ii.) Statistical analyses of the geographical distributions of petrological and chemical types among the collected specimens.

(iii.) Radiometric-dating of the dykes.

(iv.) The magnetic properties of the dykes.

(v.) Studies of individual dykes in great detail, in order to interpret the nature of their consolidation and/or intrusion.

(vi.) Detailed observations of the dykes intruded into the Central Intrusive Complexes.

(vii.) Construction of dynamic models, with a view to the interpretation of the fracture-patterns resulting from the imposition of certain stress-systems.

(viii.) Studies of the form and structure of other dyke-swarms throughout the world, by means of analyses of the amassed data of other workers.

(ix.) Original researches on other dyke-swarms, using those same techniques of observation outlined in preceding chapters.

17:II. Statistical Analyses of Numerical Data.

Techniques of computer-analysis would be useful in assessing the limits of error in all the calculations and assumptions described in this thesis. The degree of approach of the swarms towards a perfect linear-type might be assessed on a purely statistical basis. A procedure adopted by Frost (1965), for centre-finding in the radial dykes of Lyttelton volcano (New Zealand), using an electronic digital computer, might be applied with profit to analyses involving certain dykes of Skye and Rhum.

Pure statistics and the study of dyke-swarms were deemed incompatible in certain respects in Chapter Five (III). If, however, all the variables to which a dyke is subject could be evaluated, analyses by electronic-computer, in dealing with individual dykes, would perhaps be fruitful. Provided that the mathematical model were suitable, an unprejudiced treatment of the data could be pursued, although certain bias, of course, attends the initial selection of traverses. Possibilities which come to mind are appraisals, by programmed analyses, of the geographical distributions and inter-relations of the trend, dip, and thickness of the dykes.

17:III. Petrology and Chemistry.

The petrographical and chemical analyses of the collected specimens could be used to determine the possible existence of specific patterns of geographical distribution of rock-types. Studies of the variations throughout the dykes of the swarms of (a.) petrographic rock-type, (b.) whole-rock chemistry, including perhaps a determination of the specific-gravities of the specimens, (c.) trace-element chemistry, (d.) grain-size of the whole-rock or ground-mass, and (e.) composition, size and shape of the phenocrysts, might reveal such patterns. As results definition of subswarms and secondary-swarms, recognition of phases of dyke-intrusion, and an insight into the composition of the parental magma or the reality of local reservoirs, might all be made more clear.

The connotation in all these cases includes the factor of age-relations. This is not the only point for consideration, for significant correlations of the petrology and chemistry of the dykes with their respective thicknesses, trends and dips may follow from the analyses. The significance of the geological settings of the dykes, i.e. in relation to their proximity to dilation-axes and Central Complexes, and with regard to contamination of the parent-magma during ascent through the country-rock, may also be assessed.

17:IV. Radiometric-Dating.

Dating of a large enough sample of the dykes of the individual swarms would indicate the duration of the period of intrusion. Dating of very many specimens would again be of use in separation of secondary-swarms, subswarms, periods of local injection of dyke-sets, etc.

Solutions of the questions of variability of position of the main axes of high-intensity, and of the possible systematic variation of the trends of the dykes, throughout the total time-span of intrusion, would be of great assistance in the unravelling of the sequence of events and the determination of the precise origin of the swarms. Some evidence on the method of propagation of the swarm might be acquired; for example dykes at one end of a swarm (e.g. in northern Skye) might be demonstrably older than those at the other extremity (e.g. in Sunart), or vice versa.

17:V. Magnetization.

The Geophysics Department of Liverpool University (Chadwick Laboratory) is engaged in an analysis of the remanent magnetization of the dykes outcropping in Skye (R.L. Wilson,1971). Specimens were taken in the summer of 1968, from the dykes outcropping on the southern coast of Skye from the Point of Sleat to Kyle Rhea, and from the dykes on the west coast of Vaternish headland. Similar work has been carried out on the north coast of Mull (Ade-Hall et al., 1972).

The portions sampled of the Mull and Skye swarms contain about 25 per cent. (each) of Normally magnetized dykes, whereas all the lavas of the British Tertiary Province so far examined are Reversely magnetized (R.L. Wilson,1971). Wilson believed that the Reversed dykes and the lavas were of simultaneous formation, and the Normal dykes belong to some different period. It would be interesting to assess the significance of any geographical distribution patterns of Normal and Reversed magnetization of the dykes of Skye.

17:VI. Consolidation and Intrusion of the Dykes.

A more intensive search for, and a subsequent statistical analysis of the orientations of, flow-structures in the dykes, especially in the trachytic varieties of southern Skye, is one possible course of study under this head.

Platten and Watterson are at present engaged in a study of crystallization phenomena in dykes of Strathaird and Sleat. Platten and Watterson (1969) noted that elongate crystals of clinopyroxene, plagioclase and olivine, which succeed each other (with some overlap) inwards towards the centre of the dyke, are found in layers parallel to the margins of some dykes, and are oriented at high angles to these layers. They explained that persistent flow of material along the fissure led to an increase in temperature at the solid-liquid interface, and that at some temperature below the liquidus of a particular phase, the rate of nucleation of that phase was effectively reduced to zero, although growth continued. Platten and Watterson (1969,p.287) concluded that, "The oriented crystals are the result of competitive crystal growth from an interface on which no nuclei are forming".

17:VII. Dykes within the Central Complexes.

For reasons mentioned earlier, studies of the dykes injected into the Central Intrusive Complexes of Skye, Ardnamurchan and Rhum, have been neglected (Ch.5:IV). It would be interesting to assess the validity of Harker's (1904,p.365) sequence of dyke-intrusion in the Cuillins — questioned by Gibb (1968) — and to correlate any of the sets Harker found (radial, tangential, etc.) with the subswarms outside the Central Complex of Skye.

17:VIII. Dynamic Models.

The construction of lacquer-coated clay-cake or gelatine models, or any other types of model (e.g. Austin,1961; Durelli et al.,1958), to resemble the postulated crustal structures in the Tertiary Hebridean Province, is itself attended by many difficulties. To produce fracture-patterns in such models, on application of controlled stress-fields, would involve a great deal of trial and error. The whole process of study of such phenomena would be almost entirely experimental. It is felt necessary, however, to offer some tentative suggestions on at least the preliminary methods of approach.

A clay-cake model, either flat or moulded into a basin-shape to simulate what is believed to be the form of the lava-pile, could be stretched under a directed tensional force. At the same time an element of shear could be introduced by relative movement of two sections of beading, the one adjacent to the other and each attached to the underside of the clay-cake. The position of such a shear is to coincide with the major axes of dilation and to represent zones of transcurrent displacement. If necessary these sections of beading could have the form of a fin-backed ridge. To further complicate matters, a position on the underside of the clay-cake could be subjected to a spasmodic vertical pressure or to a regular pulse. The position at which this pressure impinges is to coincide on the model with the location of the Central Intrusive Complex rising into the crust of the earth.

The idea for this particular model stems from a proposal by Price and Ramsay (pers. comm.). The technical difficulties involved would appear to be great but not insuperable. It would perhaps be expedient to build up the stresses on the model in the same stages followed by the above description, and observe the results at each. A further intricacy, entailing a variation in the direction of applied tension, might also be introduced.

17:IX. Data on Other Dyke-Swarms.

A certain amount of data on many of the dyke-swarms of the world has undoubtedly been accumulated. The data on which many authors base their findings is rarely presented in print. It would give great personal satisfaction if, on acquisition of such data, its treatment by those methods employed in this thesis yielded equally or more illuminating results.

17:X. Original Study of Other Dyke-Swarms.

A dyke-swarm most appropriate to a study of the type described in preceding chapters of this work is a well-exposed, young, and little-disturbed regional-swarm. The lack of any great extent of exposure in the vertical-sense, in the Hebridean swarms, has been a constant inconvenience and has impeded many useful analyses. The study of a dyke-swarm in a topographically deeply-dissected region would possibly be of great profit, e.g. the dyke-swarm of Madeira. Indeed, a study of the Madeiran dyke-swarm, set as it is in the background of a rift system, would possibly lead to an increased understanding of the relation of major crustal structures to the emplacement of dyke-swarms.

For original researches on other dyke-swarms there is no need, however, to look quite so far afield as Madeira, for the Tertiary dyke-swarms of northern Ireland are as yet poorly documented. Researches have been carried out on the Tertiary dyke-swarm of Mull (Sloan,1970), and work on the swarms of Arran and Islay-Jura is in progress(Knaap). Although exposures are of very much poorer quality in Ireland than along the deeply-etched coasts of the Hebrides, it seems that the researches on the Tertiary dyke-swarms of the British Isles can be considered fully comprehensive only when these Irish swarms have been studied in as much detail as exposures permit.

APPENDICES

Alphabetical List of Abbreviations used in Appendices

A	...	"Abnormal"
Arithm. Avge.	...	Arithmetic-Average
CC or Cc ...	...	cross-cutting strike of foliation of Moine <u>or</u> cross-cutting strike-slip joints of Torridonian
deg. ...	...	degrees
deg. of comp.	...	degrees of compass
En.	...	eastern
ex. <u>or</u> excl.	...	excluding
interv's ...	...	intervals
km.	...	kilometre
L.	...	Loch
m.	...	metre
max. ...	...	maximum
PL <u>or</u> Pl ...	...	parallel to strike of foliation of Moine <u>or</u> parallel to strike-slip joints of Torridonian
N.	...	"Normal"
N.E. ...	...	north-east
Nn.	...	northern
No.	...	number
No./km. ...	...	number per kilometre
%n	...	percentage by summated number
%t	...	percentage by summated thickness
Sn.	...	southern
S.W. ...	...	south-west
Sxn. ...	...	section
Thickn. ...	...	thickness
Vert. ...	...	vertical
Wn.	...	western

Appendix 1

AREAS	TRENDS	Average
Narrows of Raasay	15,33,28,36,24	27
Sligachan	50,23,41,68,41	45
Scalpay	80,35,36,40,30	44
"	37,24,48,48,40	39
"	38,35,26,39,53	38
"	42,27,42,28,56,30,30	37
"	25,30,83,68,65	54
Rudh' an Eireannaich	98,95,95,53	85
Broadford	65,61,70,53,76,78	67
"	50,71,53,88	66
"	78,91,86,86	85
Pabay	58,28,73,86,92,92,98	75
"	85,85,24,76,83	71
"	38,60,95,74,30	59
"	70,45,25,46,48	47
Rubh Suisnish	71,71,45,45,45	55
" "	67,67,40,93	67
Applecross	2,15,15,25,27	17
"	15,40,26,17,33	26
"	50,35,35,35	39
"	35,52,44,44,79	51
"	38,46,14,22,12	26
"	10,17,48,22	24
Torridon	24,25,10,15	19
"	17,43,36,46	36
"	15,9,360,358,358	4
"	12,28,44,7,26	23
"	29,34,23,17,33	27
Crowlin Island	29,22,72,48,68	48
" "	12,14,87,59,49	44
" "	53,31,42,53,62	48
" "	30,39,52	40

Appendix 2

Grid-References of End-Members			The Trends of ten dykes (Deg. of compass)	Arithm. Average Trend (deg of comp.)
379189	-	413198	61,25,93,83,97,43,66,38,39,97	64
413198	-	412190	73,73,85,68,86,90,82,82,48,63	75
412190	-	402177	98,93,53,91,77,37,53,53,38,55	65
400175	-	392167	50,60,95,86,63,98,49,78,73,60	71
391165	-	390160	35,21,30,48,81,29,91,65,50,51	50
392160	-	414165	61,51,46,32,27,41,40,60,55,40	45
416165	-	432169	37,35,31,33,51,41,33,30,38,35	36
432169	-	445171	38,36,43,21,21,20,24,35,35,35	31
445171	-	509184	35,55,51,88,93,95,40,72,79,21	63
446122	-	447152	19,21,22,28,22,26,28,22,17,42	25

Appendix 3

	GROUPS 100's & 50's	ARITHMETIC MEAN (DEGREES)	MEDIAN (degrees)	GEOMETRIC MEAN (degrees)	NORMAL / ABNORMAL	STANDARD DEVIATION $S_{10°}$
1A	Duirnish	322	323	320-329	N	11·6
1B	L. Dunvegan	329	329	325-334	N	14·8
2	Vaternish	325	326	320-329	N	9·4
3	Greshornish	339	339	335-344	N	9·6
4A	Rubha Hunish	332	327	335-344	A	11·8
4B	Trotternish	334	336 / 337	330-339	N	13·3
5A	Snizort	338	339 / 340	335-344	N	20·3
5B	Portree	342	341 / 344	330-339 / 345-354	A	15·9
6	Roag	327	327	320 - 329	N	11·5
7	Harlosh	319	319	315 - 324	N	8·5
8	Ullinish	323	321	320 - 329	N	11·3
9	Harport	328	330	325 - 334	N	12·7
10	Eynort	318	316	310 - 319	N	18·3
11	Sligachan &tc.	338	340	345 - 354	A	24·6
12	Ainort &tc.	321	321	310 - 319	A	22·2
13	Streams I	326	324	320 - 329	N	14·7
14	" II	323	324	320 - 329	N	12·7
15	" III	326	327	325 - 334	N	10·5
16	" IV	338	340	335 - 344	N	18·8
17	" V	329	328	320 - 329	N	12·8
18	Brittle I	318	316	315 - 324	N	23·4
19	" II	327	329	310 - 319	A	26·7
19A	Soay Sound	333	324 / 325	300-309 / 320-329 / 5-14	A	23·3
20	Soay	326	322	300 - 309	A	22·6
21	Ulfhart	334	335	325-334 / 330-339	N	17·4
22	L.na Cuilce	321	317	300 - 309	A	19·2
23	Cuillin	335	335	330 - 339	N	10·5
24	Wn. Strathaird I	330	333	330 - 339	N	8·3
25	" II	330	327	320 - 329	A	10·9
26	" III	331	329 / 330	325 - 334	N	10·8
27	Sn. Strathaird	330	328	320-329 / 325-334	N	10·2
28	En. Strathaird I	332	334	330 - 339	N	10·6
29	" II	331	328	320 - 329	A	11·7
30	" III	331	330	325 - 334	N	6·6
31	" IV	331	330	325 - 334	N	8·8
32	" V	326	328	325 - 334	N	10·8
33	" VI	319	320	320 - 329	A	12·9
34	Rubha Suisnish	329	328	325 - 334	N	18·7
35	L. Eishort	329	330	325 - 334	N	15·0

Appendix 3 (contd.)

	GROUPS 100's & 50's	ARITHMETIC MEAN (DEGREES)	MEDIAN (degrees)	GEOMETRIC MEAN (degrees)	NORMAL / ABNORMAL	STANDARD DEVIATION $S_{10°}$
36	Nn. Sleat I	341	340	335 - 344	N	12·4
37	" II	334	336	335 - 344	A	12·8
38	" III	341	340	335-344 / 340-349	N	9·0
39	" IV	338	334	330 - 339	N	10·1
40	" V	328	332	330 - 339	A	12·4
41	Sn. Sleat I	338	339 / 340	330-339 / 345-354	A	17·7
42	" II	336	338	340 - 349	A	14·8
43	" III	339	338	335 - 344	N	15·0
44	" IV	339	340	335 - 344	N	16·6
45	Broadford	326	325	320 - 329	N	17·5
46	Waterloo &tc.	323	323	335 - 344	A	22·1
OA	Raasay	342	344 / 345	345 - 354	A	17·3
OB	West Soay	316	309	300 - 309	A	21·8
OC	Glenelg	330	326	315 - 324	A	20·0
OD	Inverie	324	332 / 334	340 - 349	A	30·8
OE	L. Nevis	336	340 / 346	005 - 014	A	33·6
OF	Mallaig	354	352 / 356	360 - 009	A	26·1
OG	Morar	337	342 / 343	345-354 / 350-359	A	20·1
OH	Arisaig	352	354	360 - 009	A	15·3
OI	Rhue	350	349 / 350	340 - 349	A	16·8
OJ	Keppoch	341	342 / 344	340 - 349	N	19·4
OK	L.nan Ceall	343	343 / 344	335 - 344	A	13·1
OL	L.nan Uamh	347	349	350-359 / 355-004	A	22·3
OM	Ardnish	327	337	335 - 344	A	29·3
ON	Glenuig	353	354 / 356	355 - 004	A	17·0
OO	Moidart	358	004	005 - 014	A	21·7
OP	Arevegaig	346	351 / 352	350 - 359	A	22·8
OQ	Strontian	313	310	300-309 / 310-319	A	25·5
OR	L. Linnhe	325	322 / 324	310 - 319	A	38·2
AB	Ockle	339	334	325 - 334	A	24·8
AC	Glendrian	335	332 / 333	320-329 / 325-334	A	15·4
AD	Sanna	346	345	340 - 349	N	16·8
AE	Ormsaig	332	332	325 - 334	N	16·9
AF	Kilchoan	327	327	325 - 334	N	18·5
AG	Hiant	335	334 / 335	315 - 324	A	18·7

Appendix 4

AREA	NORTH-WEST SKYE				NORTH-EAST SKYE				SOUTH & WEST of CUILLINS			
TREND	Number	Percentage	Thickness	Percentage	Number	Percentage	Thickness	Percentage	Number	Percentage	Thickness	Percentage
085 - 089	-	-	-	-	-	-	-	-	-	-	-	-
080 - 084	-	-	-	-	-	-	-	-	-	-	-	-
075 - 079	-	-	-	-	-	-	-	-	-	-	-	-
070 - 074	-	-	-	-	-	-	-	-	-	-	-	-
065 - 069	-	-	-	-	-	-	-	-	-	-	-	-
060 - 064	-	-	-	-	-	-	-	-	-	-	-	-
055 - 059	-	-	-	-	-	-	-	-	-	-	-	-
050 - 054	-	-	-	-	-	-	-	-	-	-	-	-
045 - 049	-	-	-	-	-	-	-	-	-	-	-	-
040 - 044	-	-	-	-	-	-	-	-	-	-	-	-
035 - 039	-	-	-	-	-	-	-	-	-	-	-	-
030 - 034	-	-	-	-	-	-	-	-	-	-	-	-
025 - 029	-	-	-	-	-	-	-	-	-	-	-	-
020 - 024	-	-	-	-	3	0·5	0·95	-	-	-	-	-
015 - 019	-	-	-	-	2	-	1·83	-	14	1	7·75	1
010 - 014	-	-	-	-	4	0·5	8·10	1	19	1·5	15·65	1·5
005 - 009	5	0·5	6·00	1	10	1·5	14·31	2	22	2	11·80	1
360 - 004	-	-	-	-	23	3·5	24·91	3	23	2	18·55	2
355 - 359	5	1	3·50	0·5	27	4·5	24·63	3	30	2·5	27·60	3
350 - 354	17	2·5	17·67	2	64	10	92·17	11	36	3	24·55	2·5
345 - 349	16	2·5	20·22	2	54	8·5	83·07	10	57	5	40·40	4
340 - 344	27	4	31·07	3·5	86	14	128·84	15·5	55	5	34·40	3·5
335 - 339	58	9	82·16	9	97	15·5	131·27	16	102	8·5	79·65	8
330 - 334	113	17	132·93	15	78	12·5	127·72	15·5	104	9	86·75	8·5
325 - 329	121	18	184·43	21	68	11	75·51	9	116	10	131·62	13
320 - 324	132	20	179·87	20	44	7	49·50	6	143	12	146·20	14·5
315 - 319	74	11	104·57	12	28	4·5	23·89	3	125	10·5	106·00	10·5
310 - 314	47	7	65·89	7·5	15	2·5	16·00	2	88	7·5	75·40	7·5
305 - 309	27	4	32·80	3·5	7	1	9·35	1	96	8	78·60	7·5
300 - 304	11	2	13·46	1·5	9	1·5	13·43	1·5	66	5·5	54·85	5·5
295 - 299	5	1	9·46	1	2	0·5	1·50	-	24	2	16·50	2
290 - 294	3	0·5	5·60	0·5	5	1	4·05	0·5	22	2	13·90	1·5
285 - 289	2	-	2·23	-	-	-	-	-	23	2	17·05	2
280 - 284	1	-	1·00	-	-	-	-	-	13	1	9·45	1
275 - 279	-	-	-	-	-	-	-	-	-	-	-	-
270 - 274	-	-	-	-	-	-	-	-	-	-	-	-
TOTALS	664		892·86		626		834·08		1178		996·67	

Appendix 4 (contd.)

AREA	SOUTH-EAST SKYE				STRATHAIRD				SLEAT			
TREND	Number	Percentage	Thickness	Percentage	Number	Percentage	Thickness	Percentage	Number	Percentage	Thickness	Percentage
085 - 089	-	-	-	-	-	-	-	-	-	-	-	-
080 - 084	-	-	-	-	-	-	-	-	-	-	-	-
075 - 079	-	-	-	-	-	-	-	-	-	-	-	-
070 - 074	-	-	-	-	-	-	-	-	-	-	-	-
065 - 069	-	-	-	-	-	-	-	-	-	-	-	-
060 - 064	-	-	-	-	-	-	-	-	-	-	-	-
055 - 059	-	-	-	-	-	-	-	-	-	-	-	-
050 - 054	-	-	-	-	-	-	-	-	-	-	-	-
045 - 049	-	-	-	-	-	-	-	-	-	-	-	-
040 - 044	-	-	-	-	-	-	-	-	-	-	-	-
035 - 039	-	-	-	-	-	-	-	-	-	-	-	-
030 - 034	-	-	-	-	-	-	-	-	-	-	-	-
025 - 029	-	-	-	-	-	-	-	-	-	-	-	-
020 - 024	2	-	1·40	-	-	-	-	-	-	-	-	-
015 - 019	18	2	12·90	1·5	-	-	-	-	5	0·5	7·45	0·5
010 - 014	6	1	10·60	1	-	-	-	-	9	1	23·35	1
005 - 009	5	0·5	8·40	1	2	-	1·90	-	8	1	9·95	0·5
360 - 004	20	2·5	15·90	1·5	2	-	1·50	-	19	2	37·85	2
355 - 359	15	2	11·63	1	4	0·5	4·80	0·5	33	4	67·90	3·5
350 - 354	31	4	40·05	4	12	1	11·15	1	57	6·5	128·58	7
345 - 349	44	5·5	49·08	5	37	4	42·80	3·5	104	12	241·07	12·5
340 - 344	52	6·5	71·10	7·5	66	7	79·45	7	162	18·5	392·64	20·5
335 - 339	50	6	49·22	5	130	13·5	157·90	13·5	161	18·5	384·92	20
330 - 334	88	11	105·31	11	195	20·5	235·70	20·5	155	18	324·87	17
325 - 329	83	10·5	116·68	12	240	25	291·65	25	59	7	115·20	6
320 - 324	79	10	120·82	12·5	132	14	158·05	13·5	42	5	91·75	5
315 - 319	91	11·5	105·20	11	55	5·5	66·65	6	6	0·5	9·85	0·5
310 - 314	76	9·5	87·90	9	48	5	63·00	5·5	20	2·5	32·70	1·5
305 - 309	35	4·5	44·17	5	13	1·5	17·20	1·5	6	0·5	7·15	0·5
300 - 304	44	5·5	45·90	5	8	1	4·85	0·5	3	0·5	2·95	-
295 - 299	28	3·5	32·40	3·5	4	0·5	5·50	0·5	9	1	18·35	1
290 - 294	18	2	18·95	2	3	-	3·00	0·5	2	-	1·65	-
285 - 289	11	1·5	7·30	1	4	0·5	3·50	0·5	4	0·5	4·60	0·5
280 - 284	4	0·5	2·60	0·5	4	0·5	4·45	0·5	3	0·5	5·33	0·5
275 - 279	-	-	-	-	-	-	-	-	-	-	-	-
270 - 274	-	-	-	-	-	-	-	-	-	-	-	-
TOTALS	800		957·51		959		1153·05		867		1907·71	

Appendix 4 (contd.)

085 - 089	-	-	-	-	-	-	-	-	-	-	-	-
080 - 084	-	-	-	-	2	1	1·35	-	-	-	-	-
075 - 079	-	-	-	-	-	-	-	-	-	-	-	-
070 - 074	-	-	-	-	-	-	-	-	-	-	-	-
065 - 069	-	-	-	-	-	-	-	-	-	-	-	-
060 - 064	-	-	-	-	1	-	2·50	0·5	-	-	-	-
055 - 059	-	-	-	-	-	-	-	-	-	-	-	-
050 - 054	-	-	-	-	1	-	0·70	-	-	-	-	-
045 - 049	-	-	-	-	1	-	0·25	-	-	-	-	-
040 - 044	1	-	4·30	-	1	-	1·00	-	-	-	-	-
035 - 039	1	-	7·00	0·5	2	1	2·15	0·5	-	-	-	-
030 - 034	-	-	-	-	2	1	1·75	-	-	-	-	-
025 - 029	-	-	-	-	5	1·5	10·95	1	-	-	-	-
020 - 024	7	2	18·30	1·5	7	2	14·90	1·5	4	1	2·80	0·5
015 - 019	14	3·5	47·10	3·5	12	4	35·45	4	8	2·5	6·30	1·5
010 - 014	17	4	51·10	4	21	6·5	62·45	7	10	3	20·00	4·5
005 - 010	30	7·5	82·57	6	12	4	42·75	5	7	2	6·25	1·5
360 - 004	28	7	92·40	7	25	8	74·30	8·5	15	4·5	24·75	5·5
355 - 359	35	9	136·65	10	21	6·5	92·00	10·5	22	7	55·10	12
350 - 354	47	12	170·77	13	25	8	98·70	11·5	12	3·5	13·70	3
345 - 349	40	10	176·70	13	25	8	70·75	8	25	8	28·55	6
340 - 344	42	10·5	172·15	13	15	4·5	51·75	6	28	9	33·35	7
335 - 339	31	8	135·45	10	12	4	32·65	3·5	32	10·5	51·30	11
330 - 334	25	6	80·05	6	8	2·5	24·45	3	33	10·5	36·30	8
325 - 329	14	3·5	46·45	3·5	14	4	49·60	5·5	47	14·5	70·40	15
320 - 324	19	5	29·95	2	8	2·5	21·55	2·5	26	8	27·80	6
315 - 319	13	3	36·55	3	15	4·5	41·45	4·5	15	4·5	25·05	5·5
310 - 314	11	3	25·40	2	14	4·5	28·20	3·5	14	4·5	19·20	4
305 - 309	4	1	5·15	0·5	11	3·5	29·80	3·5	8	2·5	30·60	6·5
300 - 304	3	0·5	5·90	0·5	15	4·5	32·05	3·5	4	1	3·05	0·5
295 - 299	2	0·5	2·10	-	8	2·5	6·40	1	7	2	7·40	1·5
290 - 294	7	2	12·35	1	9	3	13·85	1·5	1	0·5	0·30	-
285 - 289	-	-	-	-	9	3	8·35	1	2	0·5	1·40	0·5
280 - 284	4	1	1·45	-	6	2	3·40	0·5	1	0·5	0·15	-
275 - 279	3	0·5	1·90	-	3	1	11·15	1·5	-	-	-	-
270 - 274	2	0·5	1·15	-	8	2·5	8·85	1	-	-	-	-
TREND / TOTALS	400		1344·04		318		875·45		321		462·85	
	Number	Percentage	Thickness	Percentage	Number	Percentage	Thickness	Percentage	Number	Percentage	Thickness	Percentage
AREA	MORAR				MOIDART & LOCH LINNHE				ARDNAMURCHAN			

Appendix 5

Trend-limits Degrees of Compass	Number of dykes	% Number of dykes	Summated Thickness of dykes (m.'s)	% Summated Thickness	Average Thickness (metres)
270 - 274	26	0·4	20·28	0·2	0·78
275 - 279	19	0·3	22·55	0·2	1·19
280 - 284	35	0·6	27·18	0·3	0·78
285 - 289	54	0·9	44·83	0·5	0·83
290 - 294	69	1·1	73·35	0·8	1·06
295 - 299	82	1·3	92·21	1·0	1·12
300 - 304	162	2·6	181·39	2·0	1·12
305 - 309	201	3·3	225·82	2·4	1·12
310 - 314	320	5·2	395·24	4·3	1·23
315 - 319	414	6·7	505·71	5·5	1·22
320 - 324	600	9·7	798·04	8·6	1·33
325 - 329	718	11·7	975·52	10·5	1·36
330 - 334	768	12·5	1119·53	12·1	1·56
335 - 339	647	10·5	1066·97	11·5	1·65
340 - 344	506	8·2	962·40	10·4	1·90
345 - 349	378	6·1	725·14	7·8	1·92
350 - 354	292	4·7	589·54	6·4	2·02
355 - 359	173	2·8	372·91	4·0	2·15
360 - 004	142	2·3	271·16	2·9	1·91
005 - 009	97	1·6	192·63	2·1	1·99
010 - 014	85	1·4	189·25	2·0	2·23
015 - 019	77	1·2	125·08	1·3	1·63
020 - 024	38	0·6	58·55	0·6	1·54
025 - 029	30	0·5	42·00	0·5	1·40
030 - 034	23	0·4	18·80	0·2	0·82
035 - 039	36	0·6	28·90	0·3	0·80
040 - 044	26	0·4	22·40	0·2	0·86
045 - 049	21	0·3	20·25	0·2	0·96
050 - 054	22	0·4	17·55	0·2	0·80
055 - 059	12	0·2	9·25	0·1	0·77
060 - 064	14	0·2	20·65	0·2	1·48
065 - 069	16	0·3	15·60	0·2	0·98
070 - 074	17	0·3	12·05	0·1	0·71
075 - 079	10	0·2	9·00	0·1	0·90
080 - 084	12	0·2	8·95	0·1	0·75
085 - 089	17	0·3	14·50	0·2	0·85
TOTALS	6159	100·0 %	9275·18 m.	100·0 %	Overall Average 1·5 m.

Appendix 6

		TREND IN DEGREES OF COMPASS																																			
		270–274	275–279	280–284	285–289	290–294	295–299	300–304	305–309	310–314	315–319	320–324	325–329	330–334	335–339	340–344	345–349	350–354	355–359	360–004	005–009	010–014	015–019	020–024	025–029	030–034	035–039	040–044	045–049	050–054	055–059	060–064	065–069	070–074	075–079	080–084	085–089
1A	Duirnish						3 (6)		10 (20)		16 (32)		14 (28)		6 (12)		1 (2)																				
1B	Loch Dunvegan				2 (4)		1 (2)		3 (6)		7 (14)		25 (50)		8 (16)		2 (4)		- (-)		2 (4)																
2	Vaternish							4		19		44		26		7																					
3	Greshornish								1		4		28		40		23		4																		
4A	Rubha Hunish									7 (14)		15 (30)		17 (34)		9 (18)		1 (2)		- (-)		1 (2)															
4B	Trotternish				1 (2)		- (-)		4 (8)		4 (8)		11 (22)		21 (42)		8 (16)		1 (2)																		
5A	Snizort							1 (2)		2 (4)		7 (14)		15 (30)		15 (30)		9 (18)		1 (2)																	
5B	Portree					1 (2)		1 (2)		1 (2)		5 (10)		13 (26)		12 (24)		10 (20)		6 (12)		1 (2)															
6	Roag				1		2		8		28		36		19		6																				
7	Harlosh					3		5		44		41		6		1																					
8	Ullinish					2		9		21		47		16		3		1		1																	
9	Harport			1		-		8		11		25		39		13		3																			
10	Eynort			5		8		17		29		21		8		6		3		1		2															
11	Sligachan and Northern Scalpay				5		4		9		14		10		13		17		12		8		8														
12	Ainort and Southern Scalpay		1		5		14		20		17		17		11		8		6		1																
13	Streams I					2		9		18		41		18		5		2		4		1															
14	Streams II			3		-		7		25		36		22		5		2																			
15	Streams III						2		10		32		40		12		3		1																		
16	Streams IV		1		-		3		8		10		19		23		19		8		8		1														
17	Streams V				1		2		6		24		32		24		10		-		1																
18	Brittle I			14		5		18		21		15		6		9		8		-		4															
19	Brittle II		3		3		9		15		16		14		5		9		10		11		5														
19A	Soay Sound						4 (8)		7 (14)		8 (16)		8 (16)		4 (8)		5 (10)		5 (10)		9 (18)																
20	Soay					7		23		16		15		8		11		11		4		5															
21	Ulfhart				3		-		8		14		24		20		16		12		3																
22	Loch na Cuilce				9		9		21		21		17		11		6		4		2																
23	Cuillin									8		22		41		20		9																			
24	Western Strathaird I							1		10		32		50		6		1																			

Appendix 6 (contd.)

		TREND IN DEGREES OF COMPASS																																			
		270-274	275-279	280-284	285-289	290-294	295-299	300-304	305-309	310-314	315-319	320-324	325-329	330-334	335-339	340-344	345-349	350-354	355-359	360-004	005-009	010-014	015-019	020-024	025-029	030-034	035-039	040-044	045-049	050-054	055-059	060-064	065-069	070-074	075-079	080-084	085-089
25	Western Strathaird II						1		1		32		34		24		6		1		1																
26	Western Strathaird III									11		39		31		14		3		2																	
27	Southern Strathaird								3		19		51		17		8		1		1																
28	Eastern Strathaird I			1		-		3		6		24		50		14		2																			
29	Eastern Strathaird II						1		3		25		37		16		17		1																		
30	Eastern Strathaird III									2		42		48		8																					
31	Eastern Strathaird IV									16		32		42		10																					
32	Eastern Strathaird V					3		3		11		42		31		10																					
33	Eastern Strathaird VI			6		1		10		29		33		17		4																					
34	Rubha Suisnish				2		4		10		20		31		15		15		2		-		1														
35	Loch Eishort						5		15		18		35		10		12		5																		
36	Northern Sleat I		1		-		-		2		1		18		41		24		12		1																
37	Northern Sleat II				1		1		6		8		28		38		15		2		1																
38	Northern Sleat III										4		14		51		27		2		2																
39	Northern Sleat IV							2		4		14		50		23		6		1																	
40	Northern Sleat V					1		-		4		7		20		40		22		6																	
41	Southern Sleat I			1		4		2		2		13		28		26		12		9		3															
42	Southern Sleat II				1		3		6		4		28		30		20		7		1																
43	Southern Sleat III		1		1		2		-		2		21		48		11		10		2		2														
44	Southern Sleat IV		2		-		2		1		7		16		39		19		6		8																
45	Broadford				5		4		11		29		25		10		9		6		-		1														
46	Waterloo and Pabay			4		12		16		15		11		17		14		4		4		3															
OA	Raasay							2 (4)		3 (6)		5 (10)		11 (22)		12 (24)		11 (22)		4 (8)		- (-)		2 (4)													
OB	West Soay		1 (2)		4 (8)		10 (20)		13 (26)		10 (20)		4 (8)		2 (4)		2 (4)		1 (2)		2 (4)		1 (2)														
OC	Glenelg					1 (2)		3 (6)		12 (24)		12 (24)		10 (20)		2 (4)		6 (12)		- (-)		3 (6)		1 (2)													
OD	Inverie		2 (4)		- (-)		4 (8)		5 (10)		8 (16)		6 (12)		10 (20)		7 (14)		1 (2)		1 (2)		- (-)		- (-)		1 (2)		- (-)		1 (2)		1 (2)		1 (2)		2 (4)
OE	Loch Nevis	1 (2)		3 (6)		5 (10)		1 (2)		4 (8)		7 (14)		3 (6)		1 (2)		3 (6)		7 (14)		11 (22)		4 (8)													
OF	Mallaig	2 (4)		- (-)		- (-)		1 (2)		4 (8)		4 (8)		8 (16)		4 (8)		4 (8)		12 (24)		9 (18)		2 (4)													

Appendix 6 (contd.)

TREND IN DEGREES OF COMPASS

		270-274	275-279	280-284	285-289	290-294	295-299	300-304	305-309	310-314	315-319	320-324	325-329	330-334	335-339	340-344	345-349	350-354	355-359	360-004	005-009	010-014	015-019	020-024	025-029	030-034	035-039	040-044	045-049	050-054	055-059	060-064	065-069	070-074	075-079	080-084	085-089
OG	Morar		2 (4)		1 (2)		1 (2)		- (-)		9 (18)		4 (8)		9 (18)		16 (32)		8 (16)																		
OH	Arisaig									2 (4)		3 (6)		5 (10)		7 (14)		14 (28)		15 (30)		4 (8)															
OI	Rhue				1 (2)		- (-)		1 (2)		- (-)		4 (8)		13 (26)		11 (22)		11 (22)		7 (14)		2 (4)														
OJ	Keppoch						2 (4)		1 (2)		6 (12)		6 (12)		13 (26)		14 (28)		2 (4)		3 (6)		2 (4)		- (-)		1 (2)										
OK	Loch nan Ceall									4 (8)		1 (2)		14 (28)		14 (28)		14 (28)		2 (4)		1 (2)															
OL	Loch nan Uamh			1 (2)		1 (2)		- (-)		4 (8)		2 (4)		7 (14)		11 (22)		12 (24)		5 (10)		4 (8)		2 (4)		- (-)		1 (2)									
OM	Ardnish	1 (2)		6 (12)		5 (10)		4 (8)		2 (4)		4 (8)		8 (16)		8 (16)		6 (12)		2 (4)		3 (6)		- (-)		- (-)		- (-)		- (-)		- (-)		- (-)		1 (2)	
ON	Glenuig							1 (2)		1 (2)		2 (4)		5 (10)		11 (22)		13 (26)		10 (20)		4 (8)		3 (6)													
OO	Moidart		1 (2)		- (-)		1 (2)		1 (2)		2 (4)		1 (2)		2 (4)		10 (20)		8 (16)		17 (34)		6 (12)		1 (2)												
OP	Arevegaig						1 (2)		5 (10)		- (-)		4 (8)		5 (10)		12 (24)		12 (24)		6 (12)		3 (6)		- (-)		- (-)		- (-)		- (-)		- (-)		- (-)		2 (4)
OQ	Strontian	5 (10)	1 (2)		5 (10)		10 (20)		8 (16)		9 (18)		2 (4)		3 (6)		3 (6)		3 (6)		1 (2)																
OR	Loch Linnhe	1 (2)		1 (2)		4 (8)		7 (14)		11 (22)		8 (16)		1 (2)		2 (4)		2 (4)		2 (4)		1 (2)		4 (8)		2 (4)		1 (2)		1 (2)		1 (2)		- (-)		1 (2)	
AB	Ockle					2 (4)		5 (10)		3 (6)		9 (18)		9 (18)		7 (14)		4 (8)		2 (4)		6 (12)		3 (6)													
AC	Glendrian						1 (2)		2 (4)		8 (16)		16 (32)		11 (22)		7 (14)		3 (6)		1 (2)		1 (2)														
AD	Sanna						1 (2)		1 (2)		1 (2)		7 (14)		12 (24)		16 (32)		5 (10)		3 (6)		4 (8)														
AE	Ormsaig				2 (4)		1 (2)		3 (6)		5 (10)		20 (40)		8 (16)		4 (8)		7 (14)																		
AF	Kilchoan			1 (2)		2 (4)		5 (10)		9 (18)		12 (24)		12 (24)		3 (6)		3 (6)		2 (4)		1 (2)															
AG	Hiant					1 (2)		2 (4)		6 (12)		12 (24)		10 (20)		5 (10)		7 (14)		6 (12)		1 (2)															

Appendix 7A

Group Code	GROUPS (50 dykes)		Percentage	Arithmetic Average Trend	TREND (Deg. of Compass) 270	280	290	300	310	320	330	340	350	360	010	020	030	040	050	060	070	080
0E	LOCH NEVIS	Total	100	336	2	6	10	2	8	14	6	2	6	14	22	8	-	-	-	-	-	-
		PL	30	005	-	-	-	-	-	-	-	2	2	10	8	8	-	-	-	-	-	-
		CC	70	326	2	6	10	2	8	14	6	-	4	4	14	-	-	-	-	-	-	-
0F	MALLAIG	Total	100	354	4	-	-	2	8	8	16	8	8	24	18	4	-	-	-	-	-	-
		PL	56	001	-	-	-	-	2	-	8	2	4	24	12	4	-	-	-	-	-	-
		CC	44	345	4	-	-	2	6	8	8	6	4	-	6	-	-	-	-	-	-	-
0G	MORAR	Total	100	337	-	4	2	2	-	18	8	18	32	16	-	-	-	-	-	-	-	-
		PL	74	343	-	-	-	-	-	12	6	14	28	14	-	-	-	-	-	-	-	-
		CC	26	320	-	4	2	2	-	6	2	4	4	2	-	-	-	-	-	-	-	-
0H	ARISAIG	Total	100	352	-	-	-	-	4	6	10	14	28	30	8	-	-	-	-	-	-	-
		PL	56	001	-	-	-	-	-	-	-	2	22	26	6	-	-	-	-	-	-	-
		CC	44	332	-	-	-	-	4	6	10	12	6	4	2	-	-	-	-	-	-	-
0I	RHUE	Total	100	350	-	-	2	-	2	-	8	26	22	22	14	4	-	-	-	-	-	-
		PL	74	353	-	-	-	-	-	-	6	20	16	18	10	4	-	-	-	-	-	-
		CC	26	342	-	-	2	-	2	-	2	6	6	4	4	-	-	-	-	-	-	-
0J	KEPPOCH	Total	100	341	-	-	-	4	2	12	12	26	28	4	6	4	-	2	-	-	-	-
		PL	16	347	-	-	-	-	-	4	2	2	-	2	4	2	-	-	-	-	-	-
		CC	84	340				4	2	8	10	24	28	2	2	2		2				
0K	LOCH NAN CEALL	Total	100	343	-	-	-	-	8	2	28	28	28	4	2	-	-	-	-	-	-	-
		PL	14	350	-	-	-	-	-	-	4	2	6	2	-	-	-	-	-	-	-	-
		CC	86	342	-	-	-	-	8	2	24	26	22	2	2	-	-	-	-	-	-	-
0L	LOCH NAN UAMH	Total	100	347	-	2	2	-	8	4	14	22	24	10	8	4	-	2	-	-	-	-
		PL	6	345	-	-	2	-	-	-	-	2	-	-	-	-	-	2	-	-	-	-
		CC	94	347	-	2	-	-	8	4	14	20	24	10	8	4	-	-	-	-	-	-
0M	ARDNISH	Total	100	327	2	12	10	8	4	8	16	16	12	4	6	-	-	-	-	-	-	-
		PL	20	331	2	4	-	2	-	-	-	2	4	-	6	-	-	-	-	-	-	-
		CC	80	326	-	8	10	6	4	8	16	14	8	4	-	-	-	-	-	-	-	-
0N	GLENUIG	Total	100	353	-	-	-	2	2	4	10	22	26	20	8	6	-	-	-	-	-	-
		PL	62	001	-	-	-	-	-	-	2	10	22	14	8	6	-	-	-	-	-	-
		CC	38	341	-	-	-	2	2	4	8	12	4	6	-	-	-	-	-	-	-	-
0O	MOIDART	Total	100	358	-	2	-	2	2	4	2	4	20	16	34	12	2	-	-	-	-	-
		PL	68	008	-	-	-	-	-	-	-	-	8	14	34	10	2	-	-	-	-	-
		CC	32	337	-	2	-	2	2	4	2	4	12	2	-	2	-	-	-	-	-	-
0P	AREVEGAIG	Total	100	346	4	-	-	2	10	-	8	10	24	24	12	6	-	-	-	-	-	-
		PL	52	359	-	-	-	-	-	-	2	-	16	22	8	4	-	-	-	-	-	-
		CC	48	332	4	-	-	2	10	-	6	10	8	2	4	2	-	-	-	-	-	-
			Number																			
0E to 0P - Twelve groups of 50 dykes +45 dykes from Ardnamurchan & Sunart		Total:	645		6	10	13	14	26	46	62	104	133	109	80	36	3	2	-	-	-	1
		Pl.	285		1	2	1	1	1	9	20	28	59	73	61	25	3	1	-	-	-	-
		Cc.	360		5	8	12	13	25	37	42	76	74	36	19	11	-	1	-	-	-	1
RATIO Pl. : Cc. for total 645 dykes									0·04	0·24	0·48	0·37	0·80	1·92	3·21	2·27						

Appendix 7B

Group Code	GROUPS		Percentage	Arithmetic Average Trend	TREND (Degrees of Compass) 280	290	300	310	320	330	340	350	360	010	020	030
OA	RAASAY	Total	100	342	-	-	4	6	10	22	24	22	8	-	4	
		PL	22	348	-	-	-	-	-	6	8	4	4	-	-	
		CC	78	340	-	-	4	6	10	16	16	18	4	-	4	
OB	WEST SOAY	Total	100	316	2	8	20	26	20	8	4	4	2	4	2	-
		PL	28	310	-	-	6	14	6	2	-	-	-	-	-	-
		CC	72	318	2	8	14	12	14	6	4	4	2	4	2	-
20	SOAY	Total	100	326	-	7	23	16	15	8	11	11	4	5	-	
		PL	22	319	-	-	10	5	3	1	-	-	-	3	-	
		CC	78	328	-	7	13	11	12	7	11	11	4	2	-	

Appendix 8

SUBSWARM		TRENDS of Dykes of SUBSWARMS (deg. of comp.)														TOTALS	Arithm. Avge. Trend (deg. of comp)
		320 - 329	330 - 339	340 - 349	350 - 359	360 - 009	010 - 019	020 - 029	030 - 039	040 - 049	050 - 059	060 - 069	070 - 079	080 - 089	270 - 279		
Glenbrittle Subswarm	No.	-	-	-	-	-	2	15	22	12	12	10	7	8	12	100	53
	%	"	"	"	"	"	"	"	"	"	"	"	"	"	"		
Scalpay-Subswarm	No.	-	-	-	-	-	2	8	12	8	3	4	-	2	-	39	40
	%	-	-	-	-	-	5	20·5	31	20·5	7·5	10·5	-	5	-		
Broadford Bay-Applecross Subswarm	No.	2	-	-	2	4	16	16	14	18	11	8	13	8	9	121	46
	%	2	-	-	2	3	13	13	12	15	9	7	11	6	7		

Appendix 9

	Section End-Members	Grid-References	No. of dykes	Length of Sxn. (km)	Aggregate Thickn. (m.)	Dilation %	No./Km.
1	HA.16-HA.8	NG. 052827 - 063842	9	1·57	12·30	0·8	6
2	HA.7-HA.1	NG. 068849 - 086856	7	1·94	24·10	1·2	3
3	HA.17 & 18	NG. 097864 - 104867	2	0·74	4·95	0·7	3
4	Reibinish	NG. 180913 - 189918	Nil	1·03	Nil	Nil	Nil
5	NP. 1 & 2	NG. 128468 - 137475	2	1·11	4·25	0·4	2
6	GL. 4-1	NG. 135510 - 169498	4	2·86	9·80	0·3	1-2
7	D.1-12	NG. 161554 - 182559	12	2·58	29·87	1·2	5
8	LE. 1-18	NG. 226477 - 236490	19	1·27	35·32	2·8	15
9	DV.5-0	NG. 250466 - 253472	6	0·49	9·31	1·9	12
10	CB.4-16	NG. 224550 - 246557	13	2·33	28·87	1·2	6
11	ST. 1-8	NG. 264541 - 270553	8	0·96	14·24	1·5	8
12	G.20-5	NG. 250361 - 256385	16	1·21	21·63	1·8	13
13	E.5-1	NG. 255408 - 252421	5	0·57	6·40	1·1	9
14	LV. 7-1	NG. 252423 - 264421	7	0·97	7·52	0·8	7
15	PR. 33-23	NG. 266420 - 270429	11	0·67	21·15	3·2	16
16	PR.22-1	NG. 272425 - 278439	22	1·14	36·13	3·2	19
17	V. 28-5	NG. 281413 - 287427	23	1·02	22·63	2·2	23
18	V.49-30	NG. 280400 - 285413	20	0·97	22·71	2·3	21
19	V48, HP. 1-59	NG. 281400 - 301432	60	3·02	86·28	2·9	20
20	U.2[illegible]1	NG. 316366 - 321384	29	1·08	35·13	3·3	27
21	U.39 - BP. 5	NG. 315360 - 320370	16	0·79	17·37	2·2	20
22	PB. 1-27	NG. 322370 - 331372	27	0·98	49·78	5·1	28
23	PB.28-59	NG. 332372 - 346375	32	1·34	37·01	2·8	24
24	A.16-1-28	NG. 217598 - 230638	27	2·69	52·04	1·9	10
25	A.29-60	NG. 230638 - 231648	35	0·51	56·75	11·1	70
26	A.61 - B.19	NG. 232649 - 232671	17	1·08	31·68	2·9	16
27	B. 2-8	NG. 269603 - 269620	8	0·89	15·70	1·8	9
28	B. 18-9	NG. 236669 - 266636	10	1·88	24·23	1·3	5
29	LD.3-30, GR.34,(a)	NG. 328542 - 348564	33	2·65	60·52	2·3	12
30	LG.1, GR. 1-33	NG. 337531 - 350562	34	2·30	60·73	2·6	15
31	RB. 1-11	NG. 321512 - 332521	11	1·44	17·32	1·2	8
32	TV. 1-34	NG. 344515 - 365560	34	3·55	67·08	1·9	10
33	TV. 36-45	NG. 363562 - 365567	10	0·34	11·53	3·4	30
34	C.1-5	NG. 359700 - 362705	5	0·48	7·24	1·5	10
35	C.15-6	NG. 370716 - 387718	10	1·63	18·29	1·1	6
36	C.16-36	NG. 406757 - 442766	23	3·73	34·90	1·1	6
37	RA.1-6 (90%)	NG. 400648 - 406660	7	0·99	13·10	1·5	8
38	UB.1-13	NG. 381610 - 389624	13	1·21	22·76	1·9	11
39	Q.1-9	NG. 441679 - 450692	9	1·27	15·10	1·2	7
40	HI. 1 & 2 (90%)	NG. 399573 - 404577	2	0·55	4·35	ca.0·9	5

In Appendices 9, 9A and 9B, the number (90%, etc.) following the section end-members is an estimate of the amount of exposure in the section, where that exposure is less than 100 per cent.

Appendix 9 (contd.)

	Section End-Members	Grid-References	No. of dykes	Length of Sxn. (km)	Aggregate Thickn. (m.)	Dilation %	No./Km.
41	RR.1-13	NG. 453547 - 466553	14	1·43	21·71	1·5	10
42	RH.1-7	NG. 428513 - 435514	7	0·74	9·01	1·2	10
43	RH. 8-16	NG. 443512 - 460518	9	1·76	12·10	1·0	7
44	LM.2-12 (90%)	NG. 452529 - 469533	11	1·72	14·67	1·0	7
45	P. 1,6, 8-21	NG. 494435 - 509453	17	2·08	27·72	1·3	8
46	PF. 1-21	NG. 492423 - 514426	22	2·10	40·84	2·0	10
47	TB. 2-7	NG. 511389 - 515389	6	0·34	6·17	1·8	18
48	PC. 20-1	NG. 517327 - 525330	20	0·82	15·20	1·9	24
49	FV. 6-1	NG. 318343 - 322343	6	0·49	4·50	0·9	12
50	FV. 7-22	NG. 323343 - 331349	16	0·86	14·95	1·7	19
51	PL.16-1	NG. 333362 - 345359	16	0·98	15·95	1·6	16
52	BM.38-16	NG. 387347 - 392347	23	0·41	14·45	3·9	62
53	BM. 1-15	NG. 393349 - 397351	15	0·52	14·35	3·1	32
54	AG. 1-54	NG. 412320 - 418323	54	0·66	48·75	7·8	86
55	TL. 3-1	NG. 305307 - 314306	3	0·93	2·60	0·3	3
56	ER. 18-1	NG. 365287 - 374293	18	1·05	17·40	1·8	17
57	EY. 40-28	NG. 344244 - 356246	13	1·24	9·30	0·8	11
58	EY. 27-1	NG. 359246 - 373247	27	1·28	18·65	1·5	21
59	KR.37-1	NG. 354228 - 372236	37	1·97	26·95	1·4	19
60	NB. 64-53	NG. 378189 - 387192	12	0·99	12·05	1·2	12
61	NB. 52-37	NG. 387192 - 394195	16	0·84	20·35	2·4	19
62	NB. 36-6	NG. 394195 - 403203	31	1·06	25·20	2·4	29
63	GB. 32-1	NG. 410187 - 414202	32	0·82	26·05	3·2	39
64	GB. 67-33	NG. 402178 - 410187	35	1·00	32·15	3·2	35
65	GB. 80-68	NG. 394173 - 402178	13	1·00	15·35	1·5	13
66	GB. 93-81	NG. 387162 - 394173	13	1·00	14·90	1·5	13
67	GP. 1-4	NG. 387161 - 398161	4	1·07	4·40	0·4	4
68	GP. 5-18	NG. 398161 - 410163	14	1·16	12·80	1·1	12
69	GP. 19-37	NG. 410163 - 421166	19	1·19	17·20	1·4	16
70	GP. 38-62	NG. 421166 - 432169	25	1·05	20·95	2·0	24
71	FC. 1-35	NG. 432169 - 443171	35	1·11	24·80	2·2	32
72	UL. 1-22	NG. 461172 - 472170	22	0·85	16·90	2·0	26
73	UL. 23-45	NG. 472170 - 478170	23	0·54	16·50	3·1	43
74	UL. 46-97	NG. 478170 - 484176	52	0·83	36·70	4·4	63
75	CN. 55-1	NG. 484185 - 488196	58	0·71	29·95	4·2	82
76	CN. 102-56	NG. 484176 - 484185	47	0·30	30·50	10·0	157
77	SO. 100-105	NG. 441122 - 458130	6	1·80	5·70	0·3	3
78	SO. 106-168	NG. 459142 - 473151	63	1·61	56·75	3·5	39
79	SO. 1-66	NG. 448153 - 469159	66	2·18	57·95	2·7	30
80	SO. 92-67	NG. 427146 - 447153	26	2·18	32·40	1·5	12

Appendix 9 (contd.)

	Section End-Members	Grid-References	No.of dykes	Length of Sxn.(km)	Aggregate Thickn.(m)	Dilation %	No./ Km.
81	M.11-31	NG.424253 - 426256	21	0·22	13·20	6·0	95
82	M.56-99 (90%)	NG.433258 - 439256	44	0·47	25·80	6·2	104
83	VB.1-47 (90%)	NG.425280 - 430280	47	0·50	39·65	8·8	104
84	VB.48-82	NG.430280 - 433280	35	0·37	52·10	15·8	106
85	CC.101-93	NG.454275 - 455277	9	0·07	8·55	ca.11·5	122
86	CC.68-11	NG.457282 - 462283	58	0·48	41·80	9·7	134
87	CC.10-AM.65	NG.462283 - 467287	46	0·56	36·20	6·5	83
88	AM.64-1	NG.467287 - 472291	64	0·59	39·40	6·7	92
89	AD.1-63	NG.480294 - 487299	63	0·72	35·80	5·0	87
90	RD.1-10 (excl.7)	NG.500307 - 505312	9	0·45	5·72	ca.1·3	20
91	SL 21-6,1-5	NG.546320 - 561319	21	1·35	14·54	1·1	16
92	RI.4-1 (80 %)	NG.528260 - 535266	4	0·91	4·50	0·6	5to6
93	LA.50-27	NG.545281 - 555289	24	1·27	24·80	2·0	19
94	LA.26-24,1-22	NG.555289 - 566297	25	1·29	26·32	2·0	19
95	LU.10-1,17-14, 23-18,34-24	548270 - 571288 Total of four sections	31	1·25	44·40	ca.3·6	25
96	SY.1-39	NG.580319 - 588326	39	1·02	26·95	2·6	38
97	SY.40-50	NG.589329 - 599330	11	0·96	10·55	1·1	11
98	SY.51-56	NG.599330 - 608326	6	0·73	2·85	0·4	8
99	SH.1-3 (90%)	NG.615272 - 620273	3	0·54	2·80	0·6	7
100	SH.4-11 (90%)	NG.623273 - 629278	8	1·05	7·75	0·8	11
101	SH.12-23	NG.632280 - 635287	14	0 53	13·20	2·5	26
102	PY.3-26	NG.666271 - 679279	24	1·39	32·80	2·4	17
103	PY.3,48-27	NG.670262 - 670275	23	1·42	23·85	1·7	16
104	BH.1-29	NG.643242 - 646248	29	0·38	23·27	6·2	77
105	BR.25-1	NG.656234 - 662236	25	0·68	23·55	4·0	37
106	WT.1-59	NG.662236 - 672242	57	1·06	50·45	5·1	54
107	WT.60-107	NG.672242 - 683250	48	1·30	46·82	3·6	37
108	LB.2-11	NG.688245 - 697250	10	1·03	6·20	0·6	10
109	LB.12-18	NG.697250 - 708253	7	1·16	14·20	1·2	6
110	LB.19-21	NG.708253 - 723263	3	1·91	5·65	0·3	1to2
111	KA.1	NG.749251 - 764261	1	1·73	0·25	-	-
112	CU.155-65	NG.505180 - 508182	91	0·40	62·30	15·5	225
113	CU.64-1	NG.508182 - 510185	64	0·24	48·90	20·2	264
114	WS.89*-SV.118	NG.516171 - 518180	128	0·48	113·25	23·5	299
115	WS.54-89	NG.521159 - 521163	36	0·17	36·50	21·0	207
116	EL.86-WS.47	NG.517147 - 519151	64	0·31	58·25	18·6	204
117	EL.51-85	NG.517136 - 517146	35	0·41	50·25	12·7	85
118	EL.50-2	NG.513127 - 516136	49	0·63	69·55	11·0	78
119	SA.1-39	NG.528114 - 532120	39	0·61	52·45	8·6	64
120	SA 40-79	NG.532120 - 536125	40	0·49	49·15	10·0	82

Appendix 9 (contd.)

	Section End-Members	Grid-References	No. of dykes	Length of Sxn.(km)	Aggregate Thickn.(m.)	Dilation %	No./Km.
121	GK.10-SN.40	NG.540130 - 542134	27	0·35	42·45	12·3	77
122	SN.39-NC.30	NG.542134 - 544142	69	0·46	83·80	18·2	150
123	DI.66-DR.22	NG.544142 - 548147	88	0·50	91·70	18·3	176
124	DR.23-99	NG.548147 - 550155	77	0·53	102·25	19·3	145
125	DN.1-KM.62	NG.550155 - 553160	72	0·42	107·05	25·5	171
126	KM.61-1	NG.553160 - 554166	61	0·29	68·55	23·6	210
127	CM.2-74	NG.557171 - 565174	73	0·86	102·15	11·9	85
128	CM.75-HS.42	NG.565174 - 569187	72	0·82	91·40	11·1	88
129	DL.22-1	NG.599183 - 610185	22	1·08	31·35	2·9	20
130	DL.23-59	NG.610185 - 621195	39	1·57	76·80	4·9	25
131	SU.1-50	NG.587158 - 599156	50	1·10	70·03	6·4	45
132	SU.51-88	NG.599156 - 613162	37	1·48	42·35	2·9	25
133	EH.63-16	NG.613162 - 627162	48	1·33	58·33	4·4	36
134	EH.15-1	NG.627162 - 647166	15	2·12	16·80	0·8	7
135	HE.1-22	NG.647166 - 670167	22	2·16	32·84	1·5	10
136	HE 23,24,DF4-1	NG.671166 - 679174	6	1·08	8·75	0·8	6
137	ID.94-59	NG.556038 - 561049	36	0·83	49·20	5·9	44
138	ID.58-1	NG.561049 - 574050	59	1·29	91·56	7·1	46
139	DA.1-78	NG.570059 - 576076	78	1·13	119·16	10·5	69
140	T.75-1	NG.576076 - 586085	75	1·20	186·94	15·6	63
141	TP.1-75	NG.575097 - 581107	74	0·85	132·43	15·6	87
142	OG.92-1	NG.581107 - 595115	92	1·55	170·75	11·0	59
143	TO.9-49	NG.595122 - 603128	41	1·04	70·30	6·8	39
144	TO.50-64	NG.604129 - 610130	15	0·56	22·85	4·1	27
145	OH.6-17	NG.622140 - 624144	12	0·40	16·85	4·2	30
146	OH.20,DF.32-29	NG.633150 - 638151	5	0·57	5·15	0·9	9
147	DF.29-27	NG.638151 - 659154	3	Poor Exposure. Low Intensities.			
148	DF.26-5	NG.659154 - 671176	22	1·50	25·22	1·7	15
149	PS.6-1	NM.559998 - NG.562002	6	0·46	11·15	2·4	13
150	SP.1-16	NM.561991 - 567998	16	0·79	21·10	2·7	20
151	AS.102-78	NM.571993 - 580999	23	1·12	58·60	5·2	21
152	AS.77-53	NM.580999 - NG.587004	25	0·87	65·74	7·6	29
153	AS.52-12	NG.587004 - 600007	48	1·24	117·86	9·5	39
154	AS.11-AV 85	NG.600007 - 610 011	30	1·06	108·60	10·2	28
155	AV.84-28	NG.610011 - 622017	65	1·17	216·15	18·5	56
156	AV.27-1	NG.622017 - 627026	38	0·97	109·90	11·3	39
157	AR.63-1	NG.627026 - 638039	71	1·62	194·69	12·0	44
158	AC.1-26	NG.638039 - 651059	35	1·86	76·13	4·1	19
159	AC.27-36	NG.651059 - 660071	14	1·25	31·25	2·5	11
160	KB.15-1	NG.660071 - 666087	15	1·20	36·05	3·0	13

Appendix 9 (contd.)

	Section End-Members	Grid-References	No.of dykes	Length of Sxn.(km)	Aggregate Thickn.(m.)	Dilation %	No./Km.
161	BA.1-13	NG.682084 - 703110	13	2·85	44·20	1·6	5
162	OR.3-1	NG.701115 - 713130	3	1·72	4·13	0·2	2
163	SG.1-16	NG.715147 - 726151	18	1·18	16·20	1·4	15
164	SG.17-32	NG.726151 - 734156	17	0·89	17·40	2·0	19
165	SG.33-40	NG.734156 - 749162	8	1·60	16·40	1·0	5
166	KY.5-8	NG.762173 - 775184	4	1·62	6·00	0·4	2to3
167	KY.1-4	NG.775184 - 785198	4	1·41	2·15	0·2	3
168	RV.16-1	NG.686183 - 693188	16	0·88	14·60	1·7	18
169	RY.57-67	NG.590503 - 609519	11	2·22	14·30	0·6	5
170	RY.53-43	NG.585493 - 595487	11	0·87	24·80	2·9	13
171	RY.68-78	NG.586464 - 599473	11	1·54	12·60	0·8	7
172	RY.15-2	NG.568483 - 591476	14	1·95	25·80	1·3	7
173	RY.42-16	NG.551455 - 568483	27	2·41	47·15	2·0	11
174	AX.10 & 3	NG.686461 - 702455	2	1·29	4·30	0·3	2
175	AX.13	NG.721350 - 769367	1	5·13	1·15	-	-
176	GN.28	NG.793212 - 802229	1	1·33	0·85	0·1	1
177	Totaig	NG.860250 - 873256	None	1·42	None	-	-
178	GN.6-1	NG.780164 - 798176	6	2·15	4·60	0·2	3
179	GN.16-7	NG.773153 - 780164	10	1·04	18·05	1·7	10
180	GN.22-17	NG.768140 - 773153	6	0·98	12·70	1·3	6
181	GN.27-24	NG.775124 - 815119	5	3·60	16·65	0·5	1
182	East of GN.24	NG.817118 - 832111	None	1·16	None	-	-
183	GN.35 & 34	NG.786098 - 797099	2	1·13	8·70	0·8	2
184	GN.30	NG.814091 - 827089	1	1·03	0·75	0·1	1
185	IV.23-26	NG.718053 - 739069	4	2·51	16·75	0·7	2
186	IV.12-22	NG.706042 - 718053	11	1·48	30·35	2·0	7
187	IV.5,6,10,11	NG.700030 - 706042	4	1·12	2·30	0·2	4
188	IV.2&1	NG.704018 - 716016	2	0·98	3·25	0·3	2
189	IV.37-47	NG.719027 - 737034	11	1·91	12·40	0·7	6
190	IV.34-36	NG.722001 - NM.736997	3	1·11	1·40	0·1	3
191	ML.80-92	NM.690977 - 716979	13	2·52	14·60	0·6	5
192	ML.68-78	NM.681976 - 685977	11	0·42	16·30	3·9	26
193	ML.24-18,38-48	NM.666952 - 674958	18	0·95	47·70	5·0	19
194	ML.12-4	NM.663934 - 670933	9	0·66	30·95	4·7	14
195	MO.33-15	NM.657915 - 663922	19	0·68	36·20	5·3	28
196	MO.54-34	NM.651906 - 658913	21	0·75	47·15	6·3	28
197	MO.14-3	NM.663922 - 669928	12	0·74	48·62	6·6	16
198	MO.76-61	NM.647894 - 656898	13	0·96	79·80	8·3	14
199	MO.102-88	NM.638880 - 646885	13	0·93	50·60	5·4	14
200	KE.83-65	NM.627880 - 638880	19	1·00	91·45	9·1	19

Appendix 9 (contd.)

	Section End-Members	Grid-References	No. of dykes	Length of Sxn. (km.)	Aggregate Thickn. (m.)	Dilation %	No./ Km.
201	KE.84-96	NM.641870 - 651865	13	0·80	57·05	7·1	16
202	KE.29-1	NM.611847 - 626860	28	1·50	63·10	4·2	19
203	KE.30-44	NM.626857 - 636861	15	1·06	82·50	7·8	14
204	KE.45-64	NM.639853 - 647854	15	0·77	42·80	5·6	20
205	MR.38-30	NM.612838 - 622832	9	0·80	32·70	4·1	11
206	MR.29-15	NM.622832 - 635829	15	1·06	73·60	6·9	14
207	MR.13-1	NM.635829 - 647836	13	1·42	44·75	3·1	9
208	MR.40-60	NM.650832 - 659833	21	0·76	79·30	10·5	28
209	MR.61-83	NM.659833 - 670840	23	1·32	95·75	7·3	17
210	MR.84-DD.1	NM.671837 - 684842	22	1·44	98·20	6·8	15
211	DD.11-22	NM.684838 - 702843	12	1·83	45·35	2·5	7
212	DD.23-25	NM.702843 - 713845	3	1·10	7·00	0·6	3
213	EI.22-43	NM.691806 - 711826	22	2·48	40·85	1·7	9
214	EI.44-47	NM.711826 - 731833	4	2·12	6·75	0·3	2
215	EI.21-14	NM.691806 - 718799	8	2·30	25·05	1·1	3
216	EI.62-48	NM.731795 - 752823	7	2·95	5·30	0·2	2
217	EI.5-10	NM.741801 - 752813	4	1·45	4·00	0·3	3
218	EI.2,1,3	NM.797829 - 830826	3	3·03	22·45	0·7	1
219	GU.40-37	NM.649779 - 658779	4	0·86	14·95	1·7	5
220	GU.36-23	NM.658779 - 671777	11	1·17	38·60	3·3	9
221	GU.5 1-11	NM.673777 - 685781	11	1·24	49·65	4·0	9
222	GU.12-18	NM.685781 - 697784	7	1·27	29·85	2·4	6
223	GU.19-22	NM.697784 - 713793	4	1·80	19·80	1·1	2
224	MT.41-30	NM.640757 - 665743	12	2·03	53·50	2·6	6
225	MT.29-22	NM.669740 - 679738	9	0·88	26·35	3·0	10
226	MT.21-1	NM.679738 - 697727	21	1·32	71·05	5·4	16
227	MT.73-67(excl.69)	NM.622713 - 644714	6	2·23	7·50	0·3	3
228	MT.74-82	NM.645711 - 657717	9	1·29	40·45	3·1	7
229	MT.42-53	NM.664725 - 681731	12	1·77	41·40	2·3	7
230	MT.54-66	NM.681731 - 699720	13	1·29	47·35	3·7	10
231	AK.29-37	NM.638609 - 656609	9	1·77	46·50	2·6	5
232	AK.28-22	NM.660612 - 673623	7	1·97	46·65	2·4	4
233	AK.21-18-15-17	NM.678625 - 688638	7	1·52	20·85	1·4	5
234	AK.10-2	NM.692642 - 712640	9	2·07	24·15	1·2	4
235	AK 62-59,55-58	NM.756604 - 796612	8	3·84	15·70	0·4	2
236	LT.10-1	NM.624574 - 637562	10	1·36 E/W	9·60	0·7	7
237	LT.11-14	NM.626583 - 642587	4	1·65	10·70	0·7	2
238	STR.1 & 3	NM.836637 - 864659	2	3·32	23·00	0·7,Max1·4	1
239	XY.3,1,2	NM.778597 - 806602	3	1·55	2·45	0·2	2
240	Strontian River	NM.857653 - 867660	Nil	1·21	Nil	Nil	Nil

Appendix 9 (contd.)

	Section End Members	Grid-References	No. of dykes	Length of Sxn. (km)	Aggregate Thickn. (m.)	Dilation %	No./Km.
241	STR.8-4,5	NM.825660 - 841658	5	1·34	21·85	1·6	4
242	LL.76-68	NM.746407 - 761417	9	1·80	8·40	0·5	5
243	LL.67-63	NM.761417 - 774424	5	1·41	6·60	0·5	4
244	LL.56-61	NM.774424 - 794438	6	2·37	13·75	·0·6	3
245	LL.48-46	NM.804443 - 812453	3	1·12	6·60	0·6	3
246	LL.45-41(ex.42,43)	NM.815455 - 822462	3	0·84	3·70	0·4	3
247	Loch Linnhe	NM.824468 - 836481	Nil	1·57	Nil	Nil	Nil
248	" "	NM.846498 - 850503	Nil	0·61	Nil	Nil	Nil
249	" "	NM.856514 - 857516	Nil	0·28	Nil	Nil	Nil
250	LL.36-26	NM.870524 - 882538	11	1·67	18·25	1·1	7
251	LL.25-12	NM.882538 - 889548	14	1·00	9·15	0·9	14
252	LL.1-10	NM.909553 - 946590	6	4·75	5·20	0·1	1
253	Camas Shallachain	NM.970617 - 978626	Nil	1·15	Nil	Nil	Nil
254	LIS.5	NM.783357 - 843423	1	Max.7·87	4·00	Max.0·4	Max.1
255	LIS.1 (2 sxns.)	NM.845426 - 894464	1	Max.5·47	1·30	Max.0·13	Max.1
256	LIS.6	NM.818379 - 852409	1	Max.4·07	2·60	Max.0·26	Max.1
257	Benderloch	NM.862375 - 888419	3	3·48	1·85	0·1	1
258	Appin (5sxns.)	NM.928492 - 965528	Nil	3·81	Nil	Nil	Nil

Appendix 9A

	Section End-Members	Grid-References	No. of dykes	Length of Sxn. (km)	Aggregate Thickn. (m.)	Dilation %	No./Km.
1	MI.97-92	NM.415675 - 423674	6	1·07	2·90	0·3	6
2	MI.102-107	NM.424675 - 434685	6	1·08	7·30	0·7	6
3	MI.1-15	NM.438702 - 451702	15	0·64	9·50	1·5	23
4	MI.16-44	NM.451702 - 461708	29	1·27	21·00	1·7	23
5	MI.45-79	NM.461708 - 472709	35	1·18	27·65	2·3	30
6	MI.80-91	NM.472709 - 482713	12	1·14	10·15	0·9	11
7	OK.47-38	NM.482713 - 495712	10	1·14	17·55	1·5	9
8	OK.48-52	NM.500709 - 520706	5	1·80	35·05	2·0	3
9	OK.36-20	NM.525709 - 546708	17	1·96	25·90	1·3	9
10	OK.17-15,2-11 (ex. 3,9,10)	NM.552714 - 574716	10	2·22	15·80	0·7	5
11	OK.53-58	NM.574716 - 590722	6	1·65	11·50	0·7	4
12	KL.28-26	NM.428636 - 451627	3	1·72	1·15	0·1	2
13	KL.25-10	NM.451627 - 470627	16	1·29	20·95	1·6	12
14	KL.8 - MP.68	NM.470627 - 481636	42	1·65	58·85	3·6	25
15	MP.67-49	NM.482628 - 494627	19	1·10	24·60	2·2	17
16	MP.1-48	NM.493628 - 510632	48	1·69	73·90	4·4	28
17	AK.83-64	NM.542617 - 556616	20	1·22	44·05	3·6	16
18	AK.54,53,39-44	NM.596612 - 608609	8	1·24	24·90	2·0	6
19	AK.45-52	NM.610609 - 625606	8	2·12	22·60	1·1	4

Appendix 9B

	Sxn. End-Mmbrs. & Average Trend	Grid - References	No. of dykes	Length of Sxn. (km.)	Aggregate Thickn. (m.)	Dilation %	No./Km.
1	R 3'''-7' (27°)	NG.519368 - 527352	5	1·57	4·00	0·3	3
2	SL 21'-1' (45°)	NG.546320 - 561319	5	1·00	3·25	0·3	5
3	SY 40'-48' (39°)	NG.591331 - 596330	6	0·56	7·90	1·4	11
4	SY. 54'-55^{v} (38·5°)	NG 602330 - 608326	9	0·61	10·10	1·7	15
5	SY. 1'-38' (40°)	NG.580319 - 588326	7	0·47	4·40	0·9	15
6	PY. 48', 1'-13 (80°)	NG.670262 - 670275	8	1·31	7·25	0·6	6
7	PY 25'-30' (61°)	NG.678281 - 680266	9	1·44	10·40	0·7	6
8	CR.5-14 (46°)	NG.690338 - 696335	10	0·68	10·55	1·6	15
9	AX.17 & 39-32 (30°)	NG.722348 - 712378	9	2·51	5·70	0·2	4
10	AX.12-1 ($^{ex}_{10,3}$) (21·5°)	NG.686461 - 702455	10	1·61	9·15	0·6	6
11	AX.49 58 ($^{ex.}_{53,54}$) (13°)	NG.704605 - 740600	8	3·62	24·95	0·7	2
12	AX.42-48 (24°)	NG.740592 - 763575	7	2·75	16·10	0·6	3
13	GB.80'-GP.2'' (56°)	NG.393172 - 398161	22	1·26	25·75	2·0	17

Appendix 10

	GROUPS 100's & 50's	Total Thickness (metres)	Arithmetic Average (metres)	Median (metres)	0·5m-Interval Geometric Mean	"Multiplicity" (per hundred)
1A	Duirnish	84·54	1·39	1·54	1·0–1·5	0
1B	L.Dunvegan	106·83	2·13	1·98	1·5–2·0	4
2	Vaternish	186·87	1·87	1·83	1·5–2·0	14
3	Greshornish	181·67	1·82	1·52	1·0–1·5	10/19 (LD/GR)
4A	Rubha Hunish	80·08	1·60	1·52	1·5–2·0	14
4B	Trotternish	90·76	1·82	1·50	1·0–1·5	0
5A	Snizort	68·84	1·38	1·36	1·0–1·5	0
5B	Portree	83·05	1·66	1·44	1·5–2·0	0
6	Roag	131·08	1·31	1·30	0·5–1·0	13
7	Harlosh	135·20	1·35	1·12	0·5–1·0	8
8	Ullinish	125·79	1·26	0·97	0·5–1·0	10
9	Harport	85·10	0·85	0·75	0·5–1·0	23
10	Eynort	80·65	0·81	0·70	0·5–1·0	4
11	Sligachan &tc.	71·99	0·72	0·60	0·5–1·0	16
12	Ainort &tc.	116·52	1·17	0·90	< 0·5	12
13	Streams I	61·65	0·62	0·55	0·5–1·0	14
14	" II	91·75	0·92	0·90	0·5–1·0	40
15	" III	76·35	0·76	0·60	0·5–1·0	38
16	" IV	73·20	0·73	0·60	0·5–1·0	34
17	" V	55·50	0·56	0·50	< 0·5	39
18	Brittle I	92·20	0·92	0·70	0·5–1·0	21
19	" II	101·90	1·02	0·75	0·5–1·0	2
19A	Soay Sound	34·85	0·70	0·65 / 0·70	0·5–1·0	10
20	Soay	92·60	0·93	0·65	0·5–1·0	12
21	Ulfhart	73·50	0·74	0·60	0·5–1·0	10
22	Loch na Cuilce	55·15	0·55	0·50	< 0·5	23
23	Cuillin	73·00	0·73	0·55	0·5–1·0	44
24	Wn.Strathaird I	73·05	0·73	0·60	0·5–1·0	62
25	" II	96·45	0·96	0·80	0·5–1·0	68
26	" III	101·85	1·02	0·90	0·5–1·0	46
27	Sn.Strathaird	136·95	1·37	1·25	0·5–1·0–1·5–2·0	48
28	En.Strathaird I	132·25	1·32	1·20	1·0–1·5	26
29	" II	116·40	1·16	1·00	0·5–1·0	45
30	" III	117·55	1·18	0·95	0·5–1·0	70
31	" IV	144·90	1·45	1·20	1·0–1·5	42
32	" V	124·30	1·24	1·20	0·5–1·0	44
33	" VI	130·10	1·30	1·20	0·5–1·0	42
34	Ra.Suisnish	127·48	1·27	1·05	1·0–1·5	28
35	L.Eishort	112·35	1·12	1·00	0·5–1·0	30

Appendix 10 (contd.)

	GROUPS 100's & 50's	Total Thickness (metres)	Arithmetic Avzrage (metres)	Median (metres)	0·5m Interval Geometric Mean	"Multiplicity" (per hundred)
36	Nn. Sleat I	153·41	1·53	1·20	1·0 - 1·5	17
37	" II	174·16	1·74	1·35	0·5 - 1·0	50
38	" III	212·45	2·12	1·65	1·5 - 2·0	45
39	" IV	185·32	1·87	1·50	1·5 - 2·0	52
40	" V	166·70	1·67	1·50	0·5-1·0,1·5-2·0	16
41	Sn. Sleat I	235·98	2·36	1·95	1·5 - 2·0	30
42	" II	330·77	3·31	2·70	2·0 - 2·5	45
43	" III	288·85	2·89	2·10 / 2·20	2·0 - 2·5	42
44	" IV	229·37	2·29	1·80 / 1·90	0 - 0·5 - 1·0	21
45	Broadford	89·67	0·90	0·60	< 0·5	19
46	Waterloo &tc.	103·97	1·04	0·90	0·5 - 1·0	33
OA	Raasay	93·00	1·86	1·05 / 1·10	0·5 - 1·0	12
OB	West Soay	62·60	1·25	1·00	1·0 - 1·5	8
OC	Glenelg	62·29	1·24	1·00	0·5	34
OD	Inverie	78·15	1·56	0·70/ 0·80	0·5 - 1·0	0
OE	L.Nevis	73·35	1·47	1·15	< 0·5	36
OF	Mallaig	142·99	2·86	1·95/ 2·15	0 - 0·5 - 1·0	18
OG	Morar	133·10	2·66	1·50	< 0·5	10
OH	Arisaig	217·45	4·35	3·65 / 4·00	3·00 - 3·50	10
OI	Rhue	153·70	3·07	2·00 / 2·10	1·5 - 2·0 - 2·5	12
OJ	Keppoch	237·65	4·75	2·90 / 3·15	1-1·5 & 2·5-3·0-3·5	18
OK	L.nan Ceall	182·85	3·66	2·65 / 2·85	1·0 - 1·5	4
OL	L.nan Uamh	194·40	3·89	4·00	4·0 - 4·5	0
OM	Ardnish	115·15	2·30	1·05 / 1·10	0·5 - 1·0	0
ON	Glenuig	188·70	3·77	3·40 / 3·50	< 0·5	8
OO	Moidart	170·15	3·40	2·50 / 2·70	1·5 - 2·0	4
OP	Arevegaig	193·60	3·87	2·15 / 2·20	0·5 - 1·0 - 1·5	12
OQ	Strontian	96·95	1·94	0·85 / 0·90	0·5 - 1·0	0
OR	L.Linnhe	70·45	1·41	0·80 / 1·00	0·5 - 1·0	0
AB	Ockle	107·65	2·15	1·00	0·5 - 1·0	4
AC	Glendrian	41·05	0·82	0·60	0·5 - 1·0	12
AD	Sanna	36·20	0·72	0·60	< 0·5	8
AE	Ormsaig	71·85	1·44	0·75 / 0·80	< 0·5	8
AF	Kilchoan	71·90	1·44	0·95 / 1·00	0·5 - 1·0	0
AG	Hiant	84·10	1·68	1·25	0·5 - 1·0 - 1·5	8

Appendix 11

	GROUPS	<0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23
		THICKNESS IN HALF-METRE & ONE-METRE INTERVALS																											
1A	DUIRNISH	6	4	13	11	9	2	3			1	1																	
1B	LOCH DUNVEGAN	1	5	5	17	7	7	2	2	3	1																		
2	VATERNISH	4	13	18	28	16	11	6		2	2																		
3	GRESHORNISH	7	20	22	21	14	7	3	1	1	1	1			1					1									
4A	RUBHA HUNISH	2	13	8	14	3	10																						
4B	TROTTERNISH	1	8	13	10	8	5	2		2	1																		
5A	SNIZORT	5	10	14	12	6	2	1																					
5B	PORTREE	6	9	10	14	2	3	2	1			2	1																
6	ROAG	16	24	19	31	4	1	2	2			1																	
7	HARLOSH	10	33	27	13	9	2	1	2	1	1	1																	
8	ULLINISH	8	42	26	14	5		1	1			1		1	1														
9	HARPORT	22	49	15	10	2	1		1																				
10	EYNORT	22	47	22	8		1																						
11	SLIGACHAN & N SCALPAY	36	41	16	4	2	1																						
12	AINORT & S SCALPAY	32	23	19	7	8	2	6			1	2																	
13	STREAMS I	40	44	12	4																								
14	" II	22	40	26	7	1	2	2																					
15	" III	32	44	15	6	1		2																					
16	" IV	35	38	20	5	1	1																						
17	" V	48	42	9				1																					
18	BRITTLE I	24	37	28	7		1		2		1																		
19	" II	19	45	16	9	4	2	2	2		1																		
19A	SOAY SOUND	15	27	7		1																							
20	SOAY	31	39	13	7	3	2	3	2																				
21	ULFHART	37	44	10	6	1			1		1																		
22	LOCH NA CUILCE	47	41	8	3	1																							
23	CUILLIN	35	48	10	2	1	1	2				1																	
24	WESTERN STRATHAIRD I	25	50	17	7	1																							
25	" " II	21	43	26	3	4		1	1					1															
26	" " III	18	35	28	14	4					1																		
27	SOUTHERN STRATHAIRD	8	24	24	24	16	3	1																					
28	EASTERN STRATHAIRD I	2	33	35	17	6	4	1				1		1															
29	" " II	11	35	25	18	6	2		1		1	1																	
30	" " III	11	40	25	9	7	4	2	2																				
31	" " IV	16	23	25	14	10	3	5	1	1				1	1														
32	" " V	12	28	24	23	8	2	1	2																				
33	" " VI	9	30	29	14	12	3	1		1		1																	
34	RUBHA SUISNISH	11	29	30	11	8	5	3	2	1																			
35	LOCH EISHORT	18	30	24	17	5	3	1	1	1																			
36	NORTHERN SLEAT I	18	17	25	15	11		4	3	3	1	1	2																
37	" " II	15	22	14	17	8	7	3	6	2	1	1	3	1															
38	" " III	14	13	12	18	10	7	9	3	3	3	4	3	1															
39	" " IV	10	20	17	21	11	5	4	3	1	2	3		3															
40	" " V	16	20	13	20	11	7	7	1	2	1	1					1												
41	SOUTHERN SLEAT I	12	11	13	15	9	8	10	2	8	2	5	2	2		1													
42	" " II	10	7	10	7	12	8	9	4	4	5	8	9	2	1		2	1			1								
43	" " III	12	11	8	10	14	6	10	3	6	5	5	4	1		2	1	1		1									
44	" " IV	15	15	9	13	10	7	13	7	4	2	1	3																1
45	BROADFORD	34	30	19	9	4	2	1				1																	
46	WATERLOO & PABAY	23	34	20	14	6			1			2																	
OA	RAASAY	8	14	10	3	2	4	2			2		3	2															
OB	WEST SOAY	13	11	14	4	2	1	2	1	1				1															
OC	GLENELG	16	8	10	9	3				2	1		1																
OD	INVERIE	12	17	7	2	3	2	3		1			1			1		1											
OE	LOCH NEVIS	15	7	11	6	3	2	2				2	2																
OF	MALLAIG	9	9	3	4	5	1	1	4	2	3	2	2	1	1	2		1											
OG	MORAR	12	10	1	7	3	1		2	4	1	2	4		1		1							1					
OH	ARISAIG	4	3		4			9	5	3	3	5	5	4		4			1										
OI	RHUE	5	6	5	7	7	4	2	2	3	1	1	2		1	1		1	1	1									
OJ	KEPPOCH	4	3	6	3	3	6	6	3	1		1	2	2		3		1	1	1	3				1				
OK	LOCH NAN CEALL	3	5	7	3	4	5	1	4	2	2	3	6	1			1	2	1										
OL	LOCH NAN UAMH	5	3	5	2	4	2	1	2	7	5	4	3	3	1	1	1			1									
OM	ARDNISH	9	13	7	4	1	2	1	1		2	5	3	1		1													
ON	GLENUIG	7	1	6	3	3	2	3	2	5	2	3	5	4	1	2	1												
OO	MOIDART	2	5	3	9	1	7	1	1	2	4	7	3	4	1														
OP	AREVEGAIG	4	8	8	3	4		2	2		4	4	2	3	1		2		1			1					1		
OQ	STRONTIAN	7	21	8	6	1				1		2				1		1	1	1									
OR	LOCH LINNHE	10	15	12	4	3	1		1	1		1	1			1													
AB	OCKLE	10	13	9	4	1	4	1		1	2	1		1		1	1								1				
AC	GLENDRIAN	14	19	9	5	2	1																						
AD	SANNA	23	15	6	4	1			1																				
AE	ORMSAIG	14	13	8	6	1	1	2	1	1	1		1				1												
AF	KILCHOAN	9	16	14	3	2	1	1				1	1	1	1														
AG	MIANT	4	13	13	5	6	2	3		2		1					1												

Appendix 12

THICKNESS in 0·25 m. Intervals	NUMBER of dykes (0·25m. intervals)	NUMBER of dykes (0·50m. intervals)	% (0·50m. intervals)
< 0·25	300	1214	19·7
0·25 - 0·50	914		
0·50 - 0·75	1096	1795	29·2
0·75 - 1·00	699		
1·00 - 1·25	797	1109	18·0
1·25 - 1·50	312		
1·50 - 1·75	396	749	12·2
1·75 - 2·00	353		
2·00 - 2·25	199	372	6·0
2·25 - 2·50	173		
2·50 - 2·75	148	208	3·4
2·75 - 3·00	60		
3·00 - 3·25	108	169	2·7
3·25 - 3·50	61		
3·50 - 3·75	77	104	1·7
3·75 - 4·00	27		
4·00 - 4·25	57	89	1·4
4·25 - 4·50	32		
4·50 - 4·75	40	66	1·1
4·75 - 5·00	26		
5·00 - 5·25	34	56	0·9
5·25 - 5·50	22		
5·50 - 5·75	25	34	0·6
5·75 - 6·00	9		
6·00 - 6·25	38	47	0·8
6·25 - 6·50	9		
6·50 - 6·75	25	31	0·5
6·75 - 7·00	6		
7·00 - 7·25	15	21	0·3
7·25 - 7·50	6		
7·50 - 7·75	13	20	0·3
7·75 - 8·00	7		
8·00 - 8·25	5	8	0·1
8·25 - 8·50	3		
8·50 - 8·75	3	3	-
8·75 - 9·00	-		
9·00 - 9·25	15	15	0·2
9·25 - 9·50	-		
9·50 - 9·75	2	5	0·1
9·75 - 10·00	3		
10·00 - 10·25	7	8	0·1
10·25 - 10·50	1		
10·50 - 10·75	2	3	-
10·75 - 11·00	1		
11·00 - 11·25	3	3	-
11·25 - 11·50	-		
11·50 - 11·75	5	6	0·1
11·75 - 12·00	1		

THICKNESS in 0·25 m. Intervals	NUMBER of dykes (0·25m. intervals)	NUMBER of dykes (0·50m. intervals)	% (0·50m. intervals)
12·00 - 12·25	4	4	0·1
12·25 - 12·50	-		
12·50 - 12·75	2	2	-
12·75 - 13·00	-		
13·00 - 13·25	4	4	0·1
13·25 - 13·50	-		
13·50 - 13·75	1	2	-
13·75 - 14·00	1		
14·00 - 14·25	1	1	-
14·25 - 14·50	-		
14·50 - 14·75	1	1	-
14·75 - 15·00	-		
15·00 - 15·25	3	3	-
15·25 - 15·50	-		
15·50 - 15·75	1	1	-
15·75 - 16·00	-		
16·00 - 16·25	-	-	-
16·25 - 16·50	-		
16·50 - 16·75	-	-	-
16·75 - 17·00	-		
17·00 - 17·25	-	-	-
17·25 - 17·50	-		
17·50 - 17·75	1	1	-
17·75 - 18·00	-		
18·00 - 18·25	-	-	-
18·25 - 18·50	-		
18·50 - 18·75	1	1	-
18·75 - 19·00	-		
19·00 - 19·25	-	-	-
19·25 - 19·50	-		
19·50 - 19·75	-	-	-
19·75 - 20·00	-		
20·00 - 20·25	2	2	-
20·25 - 20·50	-		
20·50 - 20·75	-	-	-
20·75 - 21·00	-		
21·00 - 21·25	-	-	-
21·25 - 21·50	-		
21·50 - 21·75	-	-	-
21·75 - 22·00	-		
22·00 - 22·25	-	-	-
22·25 - 22·50	-		
22·50 - 22·75	1	1	-
22·75 - 23·00	-		
TOTALS		6157	99·6

Appendix 13

TREND (Degrees of Compass)	NUMBER of Dykes (5°)	Percentage	TOTAL THICKNESS of dykes (metres) (5°)	Percentage	AVERAGE THICKNESS (m.)	NUMBER of Dykes (10°)	TOTAL THICKNESS of dykes (metres) (10°)	AVERAGE THICKNESS (m.)	NUMBER of Dykes (10°)	TOTAL THICKNESS of dykes (metres) (10°)	AVERAGE THICKNESS (m.)
270 - 274	26	0·4	20·28	0·2	0·78	45	42·83	0·95			
275 - 279	19	0·3	22·55	0·2	1·19				54	49·73	0·92
280 - 284	35	0·6	27·18	0·3	0·78	89	72·01	0·81			
285 - 289	54	0·9	44·83	0·5	0·83				123	118·18	0·96
290 - 294	69	1·1	73·35	0·8	1·06	151	165·56	1·10			
295 - 299	82	1·3	92·21	1·0	1·12				244	273·60	1·12
300 - 304	162	2·6	181·39	2·0	1·12	363	407·21	1·12			
305 - 309	201	3·3	225·82	2·4	1·12				521	621·06	1·19
310 - 314	320	5·2	395·24	4·3	1·23	734	900·95	1·24			
315 - 319	414	6·7	505·71	5·5	1·22				1014	1303·75	1·29
320 - 324	600	9·7	798·04	8·6	1·33	1318	1773·56	1·35			
325 - 329	718	11·7	975·52	10·5	1·36				1486	2095·05	1·41
330 - 334	768	12·5	1119·53	12·1	1·56	1415	2186·50	1·55			
335 - 339	647	10·5	1066·97	11·5	1·65				1153	2029·37	1·76
340 - 344	506	8·2	962·40	10·4	1·90	884	1687·54	1·91			
345 - 349	378	6·1	725·14	7·8	1·92				670	1314·68	1·96
350 - 354	292	4·7	589·54	6·4	2·02	465	962·45	2·07			
355 - 359	173	2·8	372·91	4·0	2·15				315	644·07	2·04
360 - 004	142	2·3	271·16	2·9	1·91	239	463·79	1·94			
005 - 009	97	1·6	192·63	2·1	1·99				182	381·88	2·10
010 - 014	85	1·4	189·25	2·0	2·23	162	314·33	1·94			
015 - 019	77	1·2	125·08	1·3	1·63				115	183·63	1·60
020 - 024	38	0·6	58·55	0·6	1·54	68	100·55	1·55			
025 - 029	30	0·5	42·00	0·5	1·40				53	60·80	1·15
030 - 034	23	0·4	18·80	0·2	0·82	59	47·70	0·81			
035 - 039	36	0·6	28·90	0·3	0·80				62	51·30	0·83
040 - 044	26	0·4	22·40	0·2	0·86	47	42·65	0·91			
045 - 049	21	0·3	20·25	0·2	0·96				43	37·80	0·88
050 - 054	22	0·4	17·55	0·2	0·80	34	26·80	0·79			
055 - 059	12	0·2	9·25	0·1	0·77				26	29·90	1·15
060 - 064	14	0·2	20·65	0·2	1·48	30	36·25	1·21			
065 - 069	16	0·3	15·60	0·2	0·98				33	27·65	0·84
070 - 074	17	0·3	12·05	0·1	0·71	27	21·05	0·78			
075 - 079	10	0·2	9·00	0·1	0·90				22	17·95	0·82
080 - 084	12	0·2	8·95	0·1	0·75	29	23·45	0·81			
085 - 089	17	0·3	14·50	0·2	0·85				43	34·78	0·81
TOTALS	6159	100·0	9275·18	100·0							

Appendix 14

TREND IN DEGREES OF COMPASS

THICKNESS in 0.25 METRE INTERVALS	270 - 274 deg	275 - 279 deg	280 - 284 deg	285 - 289 deg	290 - 294 deg	295 - 299 deg	300 - 304 deg	305 - 309 deg	310 - 314 deg	315 - 319 deg	320 - 324 deg	325 - 329 deg	330 - 334 deg	335 - 339 deg	340 - 344 deg	345 - 349 deg	350 - 354 deg	355 - 359 deg	360 - 004 deg	005 - 009 deg	010 - 014 deg	015 - 019 deg	020 - 024 deg	025 - 029 deg	030 - 034 deg	035 - 039 deg	040 - 044 deg	045 - 049 deg	050 - 054 deg	055 - 059 deg	060 - 064 deg	065 - 069 deg	070 - 074 deg	075 - 079 deg	080 - 084 deg	085 - 089 deg
< 0.25	2	2		2	6	3	11	13	13	24	29	23	28	27	29	21	15	7	9	10	4	4		5	1	5	1		1	1		1		2		1
0.25 - 0.50	5	4	9	13	15	20	31	29	50	65	67	99	111	78	55	60	46	28	21	13	6	16	14	6	7	9	6	3	5	4	3	5	5	1	3	2
0.50 - 0.75	8	4	10	12	15	12	36	50	60	85	122	124	126	104	72	41	39	29	28	20	16	14	8	4	5	8	5	6	8	1	5	3	3	1	4	8
0.75 - 1.00	5	4	4	9	5	13	18	25	44	53	70	100	94	75	41	36	22	7	15	10	10	5	3	3	2	3	5	3	2	2	3	1	1	2	2	2
1.00 - 1.25	2	2	7	8	9	13	24	30	53	60	83	96	89	96	60	43	32	18	12	9	4	8	2	3	4	2	4	4		1	1	5	6	3	1	3
1.25 - 1.50	1		1	3	5	3	9	10	15	21	43	42	42	36	24	16	11	5	5	1	5	1	4	2	1	3	1	1							1	
1.50 - 1.75	2	1	3	4	3	5	6	11	24	32	40	51	63	36	28	31	12	15	4	5	5	5			1	1	1	2	3	1					1	
1.75 - 2.00			1	2	3	4	7	8	14	18	48	63	52	41	25	20	14	5	8	1	7	6		1	2	1			1				1			
2.00 - 2.25	1			1	1	1	7	6	10	16	18	20	25	23	14	15	18	8	4	2	1	2		1		1		1	2	1						
2.25 - 2.50					2	2		4	5	8	19	26	30	22	26	7	9	4	2	1	2	2					1	1								
2.50 - 2.75					1	1	4	2	7	9	13	17	21	13	24	12	5	4	5	1	3			2						1	1		1	1		
2.75 - 3.00		1			1	1		2	2	3	6	8	9	5	8	6	5	1				1		1												
3.00 - 3.25					1	1	2	1	4	4	9	10	16	11	19	7	9	3	2	5	2					2										
3.25 - 3.50								2	2	3	5	6	5	7	10	8	2	3	2	2	1	2	1													
3.50 - 3.75						1		2	4	1	5	4	7	13	13	6	9	3	2		1	3	1				1					1				
3.75 - 4.00						1	1		1	2	3	2	2	6	5	1	1	1				1														
4.00 - 4.25								2	1		5	5	7	6	6	11	3	2	4		2	1	2													
4.25 - 4.50								1			1	4	3	5	2	4	3	3	1		2	2					1									
4.50 - 4.75							2	1	2	2	2	1	7	5	1	2	4	3	2	4		1														1
4.75 - 5.00											1		7	5	5	1	2	2			2		1													
5.00 - 5.25					1		1		3		1	4	4	4	5	4	3		2	1	1															
5.25 - 5.50								1	1	1		1		2	3	1	5	3	1	2	1															
5.50 - 5.75									1		3	3	4	2	3		2	2	2	1	2															
5.75 - 6.00							1					1			1	1		2	1	2																
6.00 - 6.25										2	2	3	6	2	4	6	2	3	1	2	3	1	1													
6.25 - 6.50														1	3		2	1		1				1												
6.50 - 6.75					1		1						2	4	4	4	3	2	3	1																
6.75 - 7.00									1					2	1			1	1																	
7.00 - 7.25		1										1	2	5	1	2	1		1							1										
7.25 - 7.50													1				3	1			1															
7.50 - 7.75									1	1	1	1		3		1	3	1				1														
7.75 - 8.00											1	1			3		1		1																	
8.00 - 8.25													3		1				1																	
8.25 - 8.50										2											1															
8.50 - 8.75															2			1																		
8.75 - 9.00																																				
9.00 - 9.25							1			1	2			3	3	2	2	1																		
9.25 - 9.50																																				
9.50 - 9.75															1				1																	
9.75 - 10.00																	1				1			1												
10.00 - 10.25									1						1	3		2																		
10.25 - 10.50																															1					
10.50 - 10.75																1				1																
10.75 - 11.00						1																														
11.00 - 11.25										1						1				1																
11.25 - 11.50																																				
11.50 - 11.75													2		1	1	1																			
11.75 - 12.00																1																				
12.00 - 12.25								1						1			1				1															
12.25 - 12.50																																				
12.50 - 12.75															1							1														
12.75 - 13.00																																				
13.00 - 13.25														1		1		1					1													
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14.00 - 14.25														1																					
14.25 - 14.50																																				
14.50 - 14.75										1																									
14.75 - 15.00																																				
15.00 - 15.25														1		1				1																
15.25 - 15.50																																				
15.50 - 15.75																	1																		
15.75 - 16.00																																				
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16.75 - 17.00																																				
17.00 - 17.25																																				
17.25 - 17.50																																				
17.50 - 17.75												1																							
17.75 - 18.00																																				

18.50 - 18.75 m
345°-349°

20.00 - 20.25 m.
325°-329° & 360°-004°

22.50 - 22.75 m.
320°-324°

Appendix 15

THICKNESS of DYKES of SUBSWARMS (metres)

SUBSWARMS		< 0·50	0·50 - 0·99	1·00 - 1·49	1·50 - 1·99	2·00 - 2·49	2·50 - 2·99	3·00 - 3·49	3·50 - 3·99	4·00 - 4·49	4·50 - 4·99	5·00 - 5·99	6·00 - 6·99	7·00 - 7·99	8·00 - 8·99	9·00 - 9·99	10·00 - 10·99	11·00 - 11·99	Total no. of dykes	Arithm. avge. Thickness (m.)
Glenbrittle	No.	37	44	14	2	1	-	-	-	-	-	-	1	-	-	-	1	-	100	0·80
	%	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"	"		
Scalpay	No.	13	11	9	2	-	1	1	2	-	-	-	-	-	-	-	-	-	39	0·96
	%	33·5	28·5	23	5	-	2·5	2·5	5	-	-	-	-	-	-	-	-	-		
Broadford Bay-Applecross	No.	29	41	19	16	8	-	3	1	-	1	1	-	-	-	1	-	1	121	1·22
	%	24	34	15·5	13	6·5	-	2	1	-	1	1	-	-	-	1	-	1		

Appendix 16

	South-West												DIP	North-East											
Group Codes	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85-89	VERT.	85-89	80-84	75-79	70-74	65-69	60-64	55-59	50-54	45-49	40-44	35-39	30-34
1A								1	1	4	2	8	8	11	10	4		1							
1B									1	1	5	7	12	10	7	4		3							
2								1	2	3	9	10	43	26	3		1	1	1						
3							1	3	1	3	15	33	18	12	7	6	1								
4A				1	2	1	2			3	1	2	15	8	6	5	2	2							
4B									2	2	1	2	18	11	10	2		2							
5A								1			1	7	13	12	7	4	4					1			
5B										1		2	10	8	8	10	6	4		1					
6									1	5	14	13	27	16	17	4	1	1		1					
7										2	4	21	30	18	15	8	1				1				
8											4	10	53	13	15	4			1						
9												4	42	32	19	3									
10				1		1	1	2	2	2	5	11	49	19	6	1									
·11						1		1	1	4	4	12	43	20	12	1	1								
12				1	1	1			3	8	7	15	49	6	4	3	1		1						
13							1		1	2	5	24	48	15	2		1		1						
14									1		2	13	62	17	5										
15											7	10	51	19	12		1								
16											9	10	26	27	19	2	2	1			1	3			
17											4	12	23	39	16	5		1							
18								1		9	16	29	41	3		1									
19				1	2			2	3	13	12	24	33	10											
19A				1					1	6	13	9	14	3	2		1								
20				1			2	3	4	3	10	13	41	13	5	2		2	1						
21										1	5	15	41	19	12	5	1	1							
22											3	9	53	10	5	5	8	6				1			
23										2	3	16	56	15	5	2	1								
24										1	4	8	44	28	13	2									
25					1				2		13	12	13	39	13	3			3			1			
26					1			2	1	5	4	18	17	28	8	6	4	4			2				
27								2		1	1	9	29	32	16	4		2		4					
28								2	3	2	4	11	16	36	11	9	2	2			2				
29												6	18	59	7	9	1								
30												16	24	41	12	4	1	2							
31									1		2	5	21	43	14	6	4	1	1			2			
32											1	12	11	35	24	10		1		1	2	2	1		
33											1	4	9	37	26	18			2		3				
34									1		2	1	28	22	23	11	7	1	2		1	1			
35										1	4	5	41	22	16	1	5	3			1	1			

Appendix 16 (contd.)

	South-West												DIP	North-East											
Group Codes	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85-89	VERT.	85-89	80-84	75-79	70-74	65-69	60-64	55-59	50-54	45-49	40-44	35-39	30-34
36							1	2			2	3	37	24	16	11	1	1		2					
37					1		1		2	2	1	2	26	21	17	18	4	2	2	1					
38									1	3	1		13	35	27	9	4	2	5						
39											4	2	29	21	31	12		1							
40										1	2	5	40	37	8	5	1			1					
41									1	3	7	2	27	19	17	7	5	3	1		5	3			
42								1		1	5		33	13	4	5	11	6	6	3	3	4	3	2	
43									3	1	4	1	47	21	6	5	8	1	2			1			
44				1			1	2		5	6	8	23	17	11	4	4	5	8	1	1	2	1		
45				4	4	1		3	2	1	5	5	49	10	9	3		1		1		2			
46				1					1	6	5	5	30	13	17	4	3	5	3	1	1	1	4		
OA										1	3	4	17	16	6		3								
OB						1	2		1	3	2	10	18	9	4										
OC							2	4	4	4		3	14	8	6	2	2	1							
OD									2		4	2	18	5	10	2	6		1						
OE										2	2	6	15	17	7		1								
OF										1	3	8	12	17	3		4								
OG									1		1	3	26	5	1	2	9	1	1						
OH						2	3	1		5	8	7	5	6	8	3	2								
OI			1	1			2		1	2	3	10	5	7	6	2	5	3	1	1					
OJ										1	5	4	19	7	7		2	4				1			
OK											2	3	14	7	13	1	5	2	1			1	1		
OL				1							1	5	15	13	9	2		2	2						
OM								1			2	2	21	10	11	1	1			1					
ON							1			2	2	4	10	5	8	3	5	1	5	2	1		1		
OO											2	6	12	13	7	3	2	2	1		1	1			
OP										1	5	6	12	12	4	2	1		4	1	1	1			
OQ							1		1		6	6	24	7	3		1						1		
OR										2	7	8	21	3	4		1	1	1				1	1	
AB	1			1		1		1	3		2	3	9	10	5	5	4	1	3		1				
AC											1	1	26	9	9	3		1							
AD											2	1	30	1	9	5	1	1							
AE								1	1	2		4	30	5	2	2	1		1		1				
AF				1		2	1	1		1			11	13	14	2	1		3						
AG			1		3		5				2	2	14	7	5	3	1	1	3		2	1			

Appendix 17

GROUPS	Average (mid-point cotangent) dip
1A	89° 30' N.E.
1B	88° 51' N.E.
2	89° 51' S.W.
3	89° 19' S.W.
4A	89° 15' S.W.
4B	88° 59' N.E.
5A	87° 54' N.E.
5B	85° 42' N.E.
6	89° 37' N.E.
7.	88° 56' N.E.
8	89° 9' N.E.
9	88° 44' N.E.
10	89° 4' S.W.
11	89° 55' S.W.
12	89° 3' S.W.
13	89° 39' S.W.
14	89° 56' N.E.
15	89° 37' N.E.
16	87° 59' N.E.
17	88° 46' N.E.
18	88° 27' S.W.
19	87° 20' S.W.
19A	87° 44' S.W.
20	89° 3' S.W.
21	89° 13' N.E.
22	87° 54' N.E.
23	89° 51' N.E.
24	89° 12' N.E.
25	89° 44' N.E.
26	88° 56' N.E.
27	88° 14' N.E.
28	88° 38' N.E.
29	88° 25' N.E.
30	88° 35' N.E.
31	87° 38' N.E.
32	86° 38' N.E.
33	86° 33' N.E.
34	86° 49' N.E.
35	88° 8' N.E.

GROUPS	Average (mid-point cotangent) dip
36	88° 19' N.E.
37	87° 37' N.E.
38	86° 40' N.E.
39	87° 52' N.E.
40	88° 51' N.E.
41	86° 24' N.E.
42	83° 17' N.E.
43	88° 18' N.E.
44	87° 2' N.E.
45	88° 31' S.W.
46	87° 38' N.E.
OA	89° 4' N.E.
OB	88° 36' S.W.
OC	88° 39' S.W.
OD	88° 12' N.E.
OE	89° 25' N.E.
OF	88° 13' N.E.
OG	87° 43' N.E.
OH	88° 13' S.W.
OI	89° 30' N.E.
OJ	88° 4' N.E.
OK	85° 33' N.E.
OL	88° 24' N.E.
OM	88° 41' N.E.
ON	85° 49' N.E.
OO	86° 58' N.E.
OP	87° 6' N.E.
OQ	89° 51' N.E.
OR	88° 31' N.E.
AB	89° 14' N.E.
AC	88° 35' N.E.
AD	88° 25' N.E.
AE	89° 19' N.E.
AF	89° 7' N.E.
AG	89° 59' N.E.

Appendix 18

DYKES OF SMALL ISLES — TRENDS AND DIPS IN GROUPS OF 50 DYKES

TREND (Deg. of Compass)

GROUPS	270-274	275-279	280-284	285-289	290-294	295-299	300-304	305-309	310-314	315-319	320-324	325-329	330-334	335-339	340-344	345-349	350-354	355-359	360-004	005-009	010-014	015-019	020-024	025-029	030-034	035-039	040-044	045-049	050-054	055-059	060-064	065-069	070-074	075-079	080-084	085-089
RA	1		3		8		6		11		8		8		2		2		(1)		-		-		-		-		-		-		-		-	
RB		5		3		4		7		10		5		4		4		5		1		-		(1)		-		(1)		-		-		-		-
RC	-		1		-		4		5		12		11		4		2		2		(4)		(4)		(1)		-		-		-		-		-	
RD	-		-		1		1		1		3		3		9		13		12		(2)		2)		(1)		(1)		(1)		-		-		-	
RE	(3)		(3)		(3)		(1)		-		-		-		1		2		2		9		8		6		3		3		2		3		(1)	
RF		(7)		(9)		(3)		-		(1)		(2)		-		(2)		(2)		(2)		(7)		(1)		(4)		(4)		-		-		(2)		(4)
RG		13		13		4		5		1		-		-		-		-		-		(1)		-		-		-		-		1		3		9
RH		8		7		8		14		4		1		-		(1)		-		-		(1)		(1)		-		-		(1)		-		-		4
RI		6		9		7		3		4		3		4		(1)		(1)		-		(2)		(1)		-		(1)		(1)		-		3		4
RJ		2		10		3		10		8		10		4		-		-		-		-		-		(2)		-		-		(1)		-		-
EA	-		6		10		13		8		4		5		1		1		-		-		-		-		-		-		-		-		2	
EB		2		4		2		8		11		7		7		5		1		2		1		-		-		-		-		-		-		-
EC		-		-		1		3		11		17		10		6		2		-		-		-		-		-		-		-		-		-
ED	-		-		5		9		14		19		3		4		-		-		-		-		-		-		-		-		-		-	
MA	-		-		-		2		1		15		13		16		3		-		-		-		-		-		-		-		-		-	
MB	-		-		-		3		7		10		15		9		2		3		1		-		-		-		-		-		-		-	
MC		-		-		-		2		5		19		17		7		-		-		-		-		-		-		-		-		-		-
MD	-		-		-		1		4		14		13		15		3		-		-		-		-		-		-		-		-		-	

DIP

GROUPS	South-West												Vertical	North-East											
	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85-89		85-89	80-84	75-79	70-74	65-69	60-64	55-59	50-54	45-49	40-44	35-39	30-34
RA	-	-	-	-	1	-	-	3	4	-	4	1	17	2	6	-	4	-	4	-	2	1	1	-	-
RB	-	-	-	-	-	-	2	1	1	5	6	5	14	4	1	1	4	-	3	-	1	-	-	2	-
RC	-	-	-	-	-	-	1	2	1	2	7	4	21	3	3	2	1	1	1	-	1	-	-	-	-
RD	(20-24: 1)			1	-	1	2	3	5	2	8	5	10	2	3	1	2	-	-	1	-	1	2	-	-
RE	-	-	1	1	-	1	4	3	2	4	-	2	13	5	4	4	2	-	1	1	-	1	-	-	1
RF	-	-	-	-	1	2	1	-	2	5	5	9	10	2	4	2	2	1	1	-	1	-	-	-	2
RG	-	-	-	-	-	-	3	1	4	3	7	1	15	3	3	3	5	1	1	-	-	-	-	-	-
RH	-	-	-	-	1	-	1	2	2	7	6	6	12	3	5	2	1	1	-	-	1	-	-	-	-
RI	-	-	-	1	3	2	1	-	6	2	3	-	14	3	4	3	4	2	1	-	1	-	-	-	-
RJ	-	-	-	-	-	-	-	-	6	4	6	9	18	1	2	-	2	1	1	-	-	-	-	-	-
EA	-	-	-	-	-	1	3	-	-	2	1	-	12	4	6	3	13	-	1	1	2	-	-	1	-
EB	-	-	-	-	-	-	-	1	1	-	1	-	21	3	11	1	8	1	2	-	-	-	-	-	-
EC	-	-	-	-	-	1	1	-	1	2	3	7	32	1	5	1	-	-	1	-	-	-	-	-	-
ED	-	-	-	-	-	-	-	-	1	-	4	5	26	9	4	1	-	-	-	-	-	-	-	-	-
MA	-	-	-	-	-	-	-	-	-	-	6	-	27	11	4	1	1	-	-	-	-	-	-	-	-
MB	-	-	-	-	-	-	-	-	2	1	4	2	23	9	5	-	1	2	1	-	-	-	-	-	-
MC	-	-	-	-	-	-	1	-	-	-	2	1	35	3	6	-	2	-	-	-	-	-	-	-	-
MD	-	-	-	-	-	-	1	-	2	-	6	9	26	3	2	-	1	-	-	-	-	-	-	-	-

Appendix 19

SMALL ISLES SWARM..... Trends (averages & deviations), Thicknesses (averages), Multiple dykes, dips (averages).

Not always 50 dykes (*)

GROUPS	Codes of dykes excluded	Number of dykes remaining	Arithmetic average Trend	Median Trend	Geometric mean Trend (10 deg. interval)	Normal/Abnormal (Trend)	Standard deviation of trend (10 deg. interval)	Total Thickness (metres)	Arithmetic average Thickness (metres)	"Multiplicity" (as a percentage)	Average cotangent dip
RA	RU. 446	49	315*	313*	305-319*	N*	18·9*	25·89*	0·53*	8	85° 31' NE.
RB	RU. 470, 460	48	320*	317/318*	310-319*	A*	24·9*	32·55*	0·68*	0	88°15' NE
RC	RU. 437, 435, 419, 409, 400, 399, 396, 395, 391	41	328*	328*	320-329*	N*	16·4*	28·70*	0·70*	4	89° 48'NE
RD	RU. 377, 376, 346, 88, 87, 86	44	349*	353/354*	350-359*	A*	21·6*	20·40*	0·46*	4	84° 53'SW
RE	RU. 62, 61, 58, 55, 54, 49, 45, 42, 41, 40, 38	39	29*	27*	15-24*	A*	22·4*	22·15*	0·57*	0	88° 5' SW.
RF	RU. 8, 91, 92	25	282*	284*	280-294*	N*	20·1*	16·10*	0·64*	12	88° 39'NE.
		22	24*	22*	15-24*	N*		14·20*	0·64*		
RG	RU. 173	49	284*	284*	270-279*	A*	15·1*	37·38*	0·71*	4	88°40'SW.
RH	RU. 213, 239, 246, 234	46	297*	299*	305-314*	A*	27·9*	50·20*	1·09*	4	87°0' SW
RI	RU. 132, 138, 129, 127, 147, 154, 274	43	298*	292*	280-289*	A*	23·1*	39·15*	0·91*	4	86° 4' SW
RJ	RU. 292, 310, 327	47	313*	314*	310-319*	N*	17·7*	38·10*	0·81*	6	87°36'SW
EA	None	50	307	305	300-309	N	18·8	37·95	0·76	4	82° 5' NE.
EB	None	50	323	320/321	310-319	A	22·8	46·25	0·93	0	84°23'NE
EC	None	50	331	330	325-334	N	13·0	34·27	0·69	18	88°48'SW
ED	None	50	317	319	315-324	N	9·3	56·50	1·13	8	89°54'NE
MA	None	50	335	334	325-334	A	11·5	68·80	1·38	32	89°8' NE.
MB	None	50	333	333	325-339	N	15·9	64·25	1·29	30	88°32'NE.
MC	None	50	335	334	330-339	N	9·9	62·10	1·24	24	89° 11'NE.
MD	None	50	334	335/336	335-344	A	11·6	67·80	1·36	4	88°8'SW.

Appendix 20

	SMALL ISLES DYKES.....	Trend & Thickness — relations & variations						
TREND (deg. of comp.) 5° intervals	Number of dykes	% by Number	Aggreg-ate Thickness (metres)	% by Thickness	(I) Thickness over 10° interval	Arithmetic Average Thickness	(II) Thickness over 10° interval	Arithmetic Average Thickness
270 - 274	21	2·1	10·00	1·1			26·43	0·60
275 - 279	23	2·3	16 43	1·8	33·13	0·58		
280 - 284	34	3·4	16·70	1·9			45·13	0·69
285 - 289	31	3·1	28·43	3·2	61·58	0 79		
290 - 294	47	4·7	33·15	3·7			62 62	0·77
295 - 299	34	3·4	29 47	3·4	58 92	0 88		
300 - 304	33	3·3	29·45	3·4			69·85	0·96
305 - 309	40	4·0	40·40	4·5	105·20	0·95		
310 - 314	71	7 2	64·80	7 3			110·58	0·81
315 - 319	65	6·6	45·78	5 2	105 83	0 85		
320 - 324	60	6·1	60·05	6·8			141·10	1·02
325 - 329	79	8·0	81 05	9 1	159 62	1 00		
330 - 334	81	8·2	78·57	8 8			166 49	1·12
335 - 339	68	6·9	87·92	9 9	168 07	1 38		
340 - 344	54	5·4	80·15	9 0			124 38	1 27
345 - 349	44	4·4	44·23	5 0	68 68	0 93		
350 - 354	30	3 1	24·45	2 8			36·45	0·70
355 - 359	22	2·2	12·00	1 3	32 50	0 88		
360 - 004	15	1·5	20·50	2·3			29·10	1·00
005 - 009	14	1·4	8·60	1·0	14·30	0·57		
010 - 014	11	1·1	5·70	0·6			15·25	0·59
015 - 019	15	1·5	9·55	1·1	24 82	0·71		
020 - 024	20	2·0	15·27	1·7			17·62	0·65
025 - 029	7	0·7	2·35	0·3	8·20	0·46		
030 - 034	11	1·1	5·85	0·7			10·07	0·53
035 - 039	8	0·8	4·22	0·5	6·03	0·40		
040 - 044	7	0·7	1·81	0·2			11·16	0·70
045 - 049	9	0·9	9·35	1·0	10·90	0·84		
050 - 054	4	0·4	1·55	0·2			5·65	0·57
055 - 059	6	0·6	4·10	0·5	4·78	0·53		
060 - 064	3	0·3	0·68	0·1			0·93	0·23
065 - 069	1	0·1	0·25	-	1·50	0·38		
070 - 074	3	0·3	1·25	0·1			4·10	0·45
075 - 079	6	0·6	2·85	0·3	10·15	0·56		
080 - 084	12	1·2	7·30	0·8			10·55	0·62
085 - 089	5	0·5	3·25	0·4	13·25	0·51		
TOTALS	994	100·0	887·46	100·0	Overall average thickness = 0·90 metres			

Appendix 21

SMALL ISLES SWARM.....Variations of trend and thickness for dykes of Rhum, Eigg, & Muck

	RHUM				EIGG				MUCK					RHUM		EIGG		MUCK	
Trend 5deg. interv's	No.	%n.	Thickn (m.)	%t.	No.	%n.	Thickn (m.)	%t.	No.	%n.	Thickn (m.)	%t.	Thickn 0·25m. interv's	No.	%	No.	%	No.	%
270 -	21	3·9	10·00	2·6	-	-	-	-	-	-	-	-	<0·25	91	16·8	26	11·8	12	5·6
275 -	22	4·1	15·28	4·0	1	0·5	1·15	0·6	-	-	-	-	0·25 -	148	27·3	36	16·4	28	13·0
280 -	31	5·7	15·80	4·1	3	1·4	0·90	0·5	-	-	-	-	0·50 -	173	31·9	79	35·9	40	18·5
285 -	26	4·8	23·03	6·0	5	2·3	5·40	2·8	-	-	-	-	0·75 -	38	7·0	21	9·5	23	10·6
290 -	34	6·3	22·45	5·9	13	5·9	10·70	5·6	-	-	-	-	1·00 -	45	8·3	18	8·2	36	16·7
295 -	25	4·6	17·22	4·5	9	4·1	12·25	6·4	-	-	-	-	1·25 -	8	1·5	7	3·2	12	5·6
300 -	20	3·7	19·45	5·1	11	5·0	6·80	3·6	2	0·9	3·20	1·2	1·50 -	10	1·8	5	2·3	10	4·6
305 -	18	3·3	13·00	3·4	18	8·2	20·85	11·0	4	1·9	6·55	2·4	1·75 -	5	0·9	6	2·7	17	7·9
310 -	40	7·4	39·35	10·3	23	10·5	17·75	9·3	8	3·7	7·70	2·8	2·00 -	6	1·1	6	2·7	6	2·8
315 -	29	5·4	17·28	4·5	29	13·2	20·05	10 5	7	3·2	8·45	3·0	2·25 -	2	0·4	5	2·3	7	3·2
320 -	21	3·9	20·85	5·5	22	10·0	19·35	10·2	17	7·9	19·85	7·2	2·50 -	4	0·7	2	0·9	6	2·8
325 -	21	3·9	17·60	4·6	20	9·1	21·50	11·3	36	16·7	41·15	14·8	2·75 -	-	-	1	0·5	4	1·9
330 -	29	5·4	25·25	6·6	16	7·3	11·72	6·2	35	16·2	40·70	14·6	3·00 -	-	-	1	0·5	5	2·3
335 -	16	3·0	10·52	2·8	13	5·9	9·85	5·2	37	17·1	58·15	20·9	3·25 -	1	0·2	1	0·5	1	0·5
340 -	10	1·8	9·15	2·4	10	4·5	11·05	5·8	33	15·3	48·95	17·7	3·50 -	-	-	3	1·4	4	1·9
345 -	17	3·1	10·20	2·7	8	3·6	10·60	5·6	18	8·3	22·33	8·0	3·75 -	-	-	1	0·5	-	-
350 -	13	2·4	6·05	1·6	5	2·3	2·95	1·6	11	5·1	14·35	5·2	4·00 -	3	0·6	1	0·5	1	0·5
355 -	14	2·6	5·50	1·4	4	1·8	1·65	0·9	3	1·4	3·05	1·1	4·25 -	-	-	-	-	1	0·5
360 -	12	2·2	13·80	3·6	-	-	-	-	2	0·9	1·70	0·6	4·50 -	-	-	1	0·5	1	0·5
005 -	10	1·8	5·30	1·4	2	0·9	2·85	1·5	1	0·5	0·15	0·1	4·75 -	1	0·2	-	-	-	-
010 -	10	1·8	5·30	1·4	-	-	-	-	1	0·5	0·40	0·1	5·00 -	2	0·4	-	-	-	-
015 -	12	2·2	7·40	1·9	1	0·5	0·35	0·2	-	-	-	-	5·25 -	-	-	-	-	-	-
020 -	18	3·3	11·97	3·1	-	-	-	-	-	-	-	-	5·50 -	-	-	-	-	-	-
025 -	7	1·3	2·35	0·6	-	-	-	-	-	-	-	-	5·75 -	-	-	-	-	-	-
030 -	9	1·7	4·65	1·2	1	0·5	0·60	0·3	-	-	-	-	6·00 -	-	-	-	-	1	0·5
035 -	7	1·3	4·07	1·1	1	0·5	0·15	0·1	-	-	-	-	6·25 -	-	-	-	-	-	-
040 -	5	0·9	0·91	0·2	2	0·9	0·90	0·5	-	-	-	-	6·50 -	1	0·2	-	-	-	-
045 -	8	1·5	8·55	2·2	-	-	-	-	1	0·5	0·80	0·3	6·75 -	-	-	-	-	-	-
050 -	4	0·7	1·55	0·4	-	-	-	-	-	-	-	-	7·00 -	-	-	-	-	-	-
055 -	6	1·1	4·10	1·1	-	-	-	-	-	-	-	-	7·25 -	1	0·2	-	-	-	-
060 -	2	0·4	0·60	0·2	1	0·5	0·08	-	-	-	-	-	7·50 -	-	-	-	-	-	-
065 -	1	0·2	0·25	0·1	-	-	-	-	-	-	-	-	7·75 -	-	-	-	-	-	-
070 -	3	0·6	1·25	0·3	-	-	-	-	-	-	-	-	8·00 -	1	0·2				
075 -	6	1·1	2·85	0·7	-	-	-	-	-	-	-	-	10·50 -	2	0·4				
080 -	11	2·0	6·65	1·7	1	0·5	0·65	0·3	-	-	-	-							
085 -	4	0·7	3·05	0·8	1	0 5	0·20	0·1	-	-	-	-	14·00 -					1	0·5
TOTALS	542	100·1	382·58	100·0	220	100·4	190·30	100·1	216	100·1	277·48	100·0	TOTALS	542	100·1	220	100·3	216	100·4

Appendix 22

SMALL ISLES DYKES ..... Dilation & Number per kilometre								
Code-number of section	Codes of end-members (with exclusions)	Number of dykes	Grid - References of end - members	Length of Sxn. (kilometres)	Aggregate Thickness of dykes (metres)	DILATION (%)	NUMBER per KILOMETRE	Arithm. Avge. Trend of dykes
1	CAN. 15	1	NG. 204050 - 219059	1·54	1·10	0·1	1	352
2	CAN. 16	1	NG. 233061 - 253066	2·01	11·00	0·5	<1	344
3	CAN. 14	1	NG. 204050 - 240050	3·46	0·30	v. low	<1	6
4	CAN. 5-1	5	NG. 240050 - 266049	2·56	13·60	0·53	2	2
5	CAN. 6	1	NG. 263040 - 281038	1·80	5·00	0·3	<1	4
6	CAN. 7-13	7	NG. 281038 - 292037	1·08	6·10	0·6	6	351
7	RU. 540-509	32	NM. 304998 - NG. 309001	0·49	17·07	ca 3·5	65	316
8	RU. 508-495, 439-463 (ex. 460)	38	NG. 321016 - 329025	1·13	29·12	2·6	34	318
9	RU. 464-494 (excl. 470)	30	NG. 329025 - 333032	0·79	22·20	2·8	38	322
10	RU. 438-412 (ex. 437, 435, 419)	24	NG. 339035 - 348040	1·03	14·40	1·4	23	328
11	RU. 411-369 (ex. 409, 400, 399, 396, 395, 391, 377, 376)	35	NG. 348040 - 361039	1·22	23·30	1·9	34	334
12	RU. 344-367 (excl. 346)	23	NG. 365041 - 378045	1·27	10·35	0·8	18	357
13	RU. 368, 88-84	6	NG. 378045 - 387040	1·19	1·90	0·2	5	23
14	RU. 83-77	7	NG. 393034 - 399028	1·23	2·35	0·2	6	28
15	RU. 76-72	5	NG. 399028 - 413023	1·50	4·48	0·3	3	26
16	RU. 71-65	7	NG. 413023 - 420012	1·12	3·00	0·3	6	35
17	RU. 64-57 (excl. 62, 61)	6	NG. 420012 - 423003	0·88	4·45	0·5	7	33
18	RU. 40-56 (ex. 55, 54, 49, 45, 42-40)	10	NG. 423003 - NM. 405998	1·33	5·02	0·4	8	30
19	RU. 33-24, 1-8 (ex. 33, 30, 28, 24, 5, 4, 3)	12	NM. 403993 - 415990	1·13	9·60	0·9	11	26
20	RU. 9-15	7	NM. 415990 - 425987	0·87	2·95	0·3	8	12
21	RU. 16-23, 89-92 (ex. 16, 17)	10	NM. 425987 - 422973	1·44	11·30	0·8	7	287
22	RU. 93-111 (excl. 93)	18	NM. 421972 - 419959	1·24	13·53	1·1	15	284
23	RU. 112-115, 171-192 (ex. 173)	25	NM. 418956 - 417951	0·61	11·50	1·9	41	283
24	RU. 196-238 (excl. 213)	42	NM. 416945 - 411935	1·06	50·60	4·8	40	294
25	RU. 239-269 (ex. 239, 246)	29	NM. 411935 - 402929	1·02	27·95	2·7	28	298
26	RU. 270-273, 124-154, 274-279 (ex. 135, 129, 127, 154, 274)	36	NM. 402929 - 393924	0·90	26·65	3·0	40	302
27	RU. 280-300 (excl. 292)	20	NM. 393924 - 385914	1·23	16·70	1·4	16	306
28	RU. 301-308	8	NM. 385914 - 377910	0·88	8·70	1·0	9	312
29	RU. 309-342 (ex. 310, 327, 341)	31	NM. 377910 - 367910	0·81	21·30	2·6	38	330
30	EG. 208-179 (excl. 186)	29	NM. 472887 - 472898	0·98	23·05	2·4	30	308
31	EG. 178-162 (excl. 169)	16	NM. 469902 - 475906	0·79	12·05	1·5	20	307
32	EG. 219215; 209-214	11	NM. 494868 - 492881	0·85	11·80	1·4	13	309
33	EG. 147A-154	8	NM. 490847 - 494850	0·35	13·05	ca 3·7	ca 23	342
34	EG. 7-1, 142-146	12	NM. 484839 - 487845	0·71	9·00	1·3	17	309

Appendix 22 (contd.)

Code-number of section	Codes of end-members (with exclusions)	Number of dykes	Grid - References of end - members	Length of Sxn. (kilometres)	Aggregate Thickness of dykes (metres)	DILATION (%)	NUMBER per KILOMETRE	Arithm. Avge. Trend of dykes
35	EG.15-9 (excl.8)	7	NM. 479832 - 485838	0·79	5·45	0·7	9	329
36	EG. 36-16 (excl. 17)	20	NM. 468834 - 479832	0 92	13·15	1·4	22	333
37	EG 57-37 (excl. 40)	20	NM 457836 - 468834	0·79	12·67	1·6	25	326
38	EG. 83-97 incl.80	16	NM. 438853 - 439864	0·65	20·05	3·1	25	327
39	EG.128-141, 127-120	22	NM. 440873 - 446878	0 77	24 50	3 2	29	311
40	EG. 119-104	16	NM. 446878 - 453882	0·72	16·05	2·2	22	312
41	MK.146-122	25	NM. 392798 - 398804	0 69	35·65	5·2	36	337
42	MK. 121-102	20	NM. 398804 - 402807	0 69	28·75	4·2	29	333
43	MK.88-59 (excl.84)	29	NM. 409804 - 416805	0 90	32·45	3·6	32	334
44	MK.58-34	25	NM. 416805 - 423805	0·54	35 65	6·6	46	334
45	MK. 216-192	25	NM. 396790 - 403788	0·65	33·50	5·2	39	335
46	MK. 191-147	45	NM. 417783 - 423787	0·73	64·85	8·9	62	334
47	MK. 1-33	33	NM. 424793 - 430796	0·77	34·10	4·4	43	333

Appendix 23

SMALL ISLES DYKES.....Variation of Thickness

GROUP CODES	Thickness (half-metre intervals up to 5m., metre intervals above 5m)																				Arithmetic average thickness for 50 dykes (metres).	Median thickness (metres) for 50 dykes	Geometric mean thickness for 50 dykes (half-metre interval).	"Normal"/"Abnormal" distribution
	0 - 0·49	0·50 - 0·99	1·00 - 1·49	1·50 - 1·99	2·00 - 2·49	2·50 - 2·99	3·00 - 3·49	3·50 - 3·99	4·00 - 4·49	4·50 - 4·99	5·00 - 5·99	6·00 - 6·99	7·00 - 7·99	8·00 - 8·99	9·00 - 9·99	10·00 - 10·99	11·00 - 11·99	12·00 - 12·99	13·00 - 13·99	14·00 - 14·99				
RA	28	15	4	1	-	-	1	-	1	-	-	-	-	-	-	-	-	-	-	-	0·61	0·40	0 - 0·50	A
RB	23	17	7	1	1	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	0·67	0·50	0 - 0·50	A
RC	21	21	3	2	1	1	-	-	1	-	-	-	-	-	-	-	-	-	-	-	0·50	0·50/0·60	0 - 0·50 - 1·00	N
RD	24	24	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0·45	0·50	0 - 0·50 - 1·00	N
RE	23	21	4	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0·57	0·50	0 - 0·50	A
RF	25	15	5	3	1	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	0·57	0·45/0·50	0 - 0·50	A
RG	17	25	3	2	2	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	0·75	0·60	0·50 - 1·00	N
RH	11	26	8	2	-	1	-	-	-	-	-	-	-	1	-	1	-	-	-	-	1·06	0·60	0·50 - 1·00	A
RI	28	15	3	1	-	1	-	-	-	-	-	-	1	-	-	1	-	-	-	-	0·87	0·40	0 - 0·50	A
RJ	15	19	9	3	2	1	-	-	1	-	-	-	-	-	-	-	-	-	-	-	0·81	0·55/0·60	0·50 - 1·00	N
EA	17	20	9	1	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	0·76	0·55/0·60	0·50 - 1·00	N
EB	11	23	6	5	3	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	0·93	0·65	0·50 - 1·00	N
EC	18	23	6	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0·69	0·60	0·50 - 1·00	N
ED	10	24	2	3	7	-	-	2	1	1	-	-	-	-	-	-	-	-	-	-	1·13	0·65	0·50 - 1·00	A
MA	6	16	10	9	1	2	2	2	1	1	-	-	-	-	-	-	-	-	-	-	1·38	1·10 / 1·15	0·50 - 1·00	A
MB	7	18	7	7	4	5	1	1	-	-	-	-	-	-	-	-	-	-	-	-	1·29	0·95/1·00	0·50 - 1·00	A
MC	9	9	19	6	3	2	-	1	-	-	-	1	-	-	-	-	-	-	-	-	1·24	1·05	1·00 - 1·50	N
MD	14	15	8	3	4	1	3	-	1	-	-	-	-	-	-	-	-	-	-	1	1·36	0·75	0·50 - 1·00	A

Appendix 24

Thickness 0·25m Intervals	270-274	275-279	280-284	285-289	290-294	295-299	300-304	305-309	310-314	315-319	320-324	325-329	330-334	335-339	340-344	345-349	350-354	355-359	360-004	005-009	010-014	015-019	020-024	025-029	030-034	035-039	040-044	045-049	050-054	055-059	060-064	065-069	070-074	075-079	080-084	085-089	Number	Percentage
	SMALL ISLES SWARM												Trend (deg. of compass)																									
<0·25	5	1	5	5	5	3	5	3	9	9	3	9	9	8	5	2	4	7	2	3	3	3	2	2	-	2	4	1	1	-	2	-	-	3	2	2	129	13·0
0·25-0·50	6	6	17	5	15	8	9	4	11	13	15	14	13	9	8	7	11	4	1	2	3	3	6	3	4	2	2	2	2	3	-	1	2	2	3	-	216	21·7
0·50-0·75	5	9	7	9	14	14	8	14	28	23	16	24	24	17	9	14	5	8	4	5	4	5	3	2	6	2	-	3	1	1	1	-	1	-	5	2	293	29·5
0·75-1·00	4	-	2	3	3	3	1	6	3	3	5	7	12	6	7	4	1	1	1	1	-	2	5	-	1	-	1	2	-	-	-	-	-	-	1	-	85	8·6
1·00-1·25	1	4	2	6	4	1	7	5	8	7	5	5	11	10	7	5	4	1	2	2	-	1	1	-	-	2	-	-	-	1	-	-	-	-	-	-	102	10·3
1·25-1·50	-	2	-	1	1	-	1	1	2	4	2	3	3	3	1	1	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	27	2·7
1·50-1·75	-	-	-	-	-	1	-	1	4	2	4	3	-	2	2	3	-	-	-	-	1	-	1	-	-	-	-	-	-	1	-	-	-	-	-	1	26	2·6
1·75-2·00	-	-	-	-	-	-	-	2	1	2	3	2	3	3	4	3	-	1	2	1	-	-	1	-	-	-	-	-	-	-	-	-	-	1	-	-	29	2·9
2·00-2·25	-	1	1	-	3	1	-	-	1	1	3	2	-	1	1	1	1	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18	1·8
2·25-2·50	-	-	-	-	1	1	-	2	1	1	-	2	2	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	14	1·4
2·50-2·75	-	-	-	1	-	-	-	-	1	-	2	-	1	4	-	1	1	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	12	1·2
2·75-3·00	-	-	-	-	1	-	1	-	-	-	-	1	-	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	0·5
3·00-3·25	-	-	-	-	-	-	-	1	-	-	-	1	-	1	2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	6	0·6
3·25-3·50	-	-	-	-	-	-	-	-	-	-	1	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	0·3
3·50-3·75	-	-	-	-	-	1	-	-	-	-	-	2	-	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7	0·7
3·75-4·00	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0·1
4·00-4·25	-	-	-	-	-	1	-	-	1	-	-	1	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	0·5
4·25-4·50	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0·1
4·50-4·75	-	-	-	-	-	-	-	1	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	0·2
4·75-5·00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	0·1
5·00-5·25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	1	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	3	0·3
>5¼ metres thickness	/	/	/	7·25+ (1)	/	/	8·00+ (1)	/	10·50+ (1)	/	6·50+ (1)	/	6·00+ & 10·50+	9·00+ & 14·00+	11·00+ (1)	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	>5¼ m. +9	10½+ 0·2% 7 at 0·1%
																																					Totals 994	100·0

Appendix 25

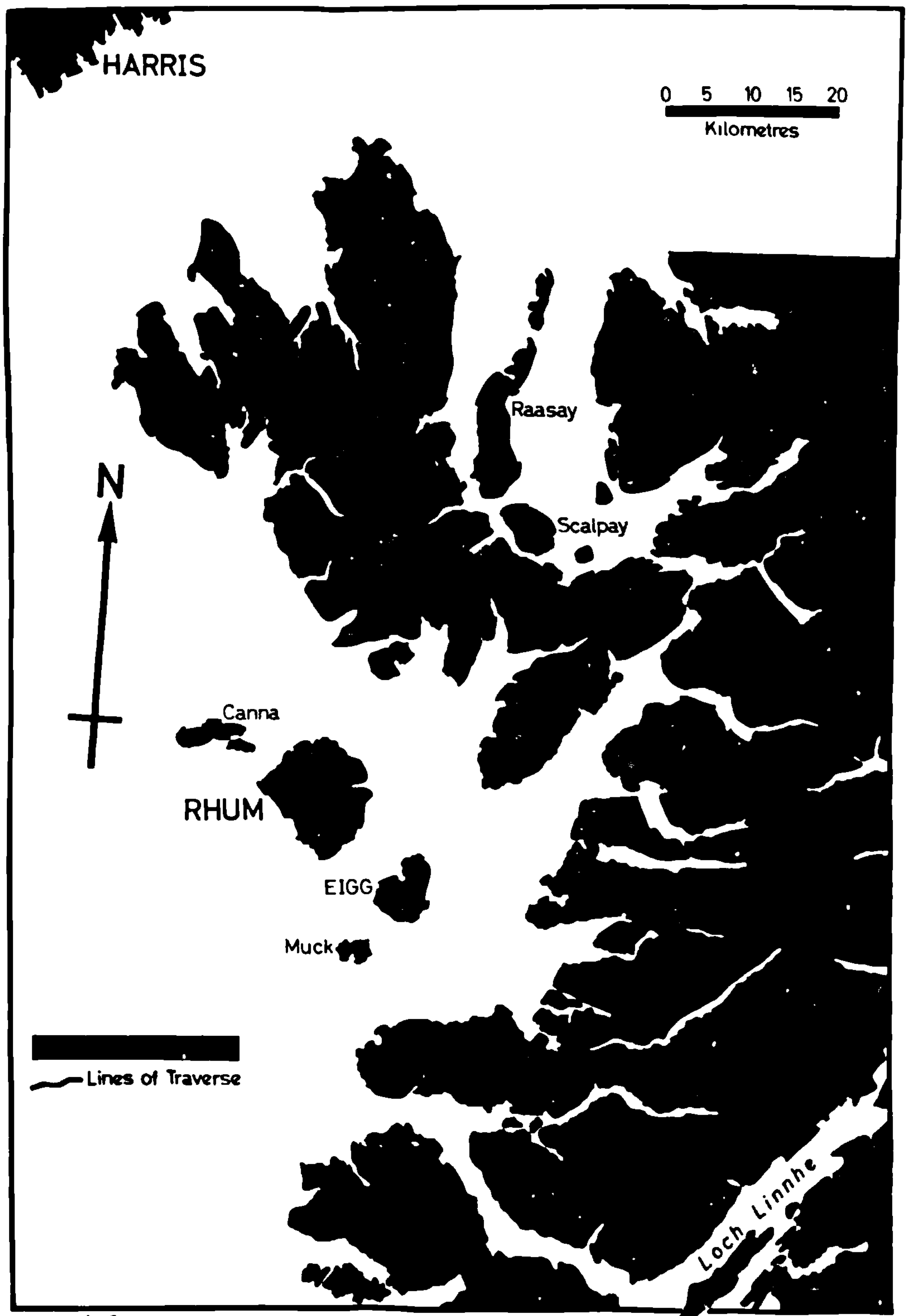

Fig.139. Locations of Traverses in the Area of Study

Appendix 26

THE PERMIAN DYKES OF NORTHERN ARGYLL AND THEIR BEARING ON POST-PERMIAN, PRE-TERTIARY DEXTRAL DISPLACEMENT ON THE GREAT GLEN FAULT.

In Morar and Arisaig (Inverness-shire) a suite of 86, chiefly lamprophyric, E. to W. trending dykes of Permian age are easily distinguished from the N. to S. trending Tertiary dolerite dykes. A linear-swarm of Permian dykes, of W.N.W. trend and extending from Ardnamurchan to Loch Linnhe, lies subparallel to the Tertiary dykes of the same region. This swarm consists of narrow lamprophyric and olivine-doleritic types (Gallagher,1963) of average thickness o.9m. The 750 dyke-outcrops observed by the present author in northern Argyll can fairly readily be distinguished from Tertiary dykes on the basis of the field-characters of the dykes (Ch.6:II).

The precise age of the so-called Permian dykes of Argyll is equivocal. It can at least be said that Holgate (1969) mistakenly identified many of these dykes as of Tertiary age. The lamprophyric and associated dykes of northern Argyll do not traverse the Mesozoic rocks and Tertiary lavas, and the camptonitic types among their number are petrographically similar to the camptonites of the Midland Valley of Scotland, which intersect the Coal Measures, and which are associated with Permian vents (Richey,1939,pp.

416-9). However, Richey (1939,pp.414-6) also drew analogies between the quartz-dolerites and tholeiites of the earlier Permo-Carboniferous suites in the Midland Valley and a few petrographically similar, sparsely distributed, W.N.W.-trending dykes in Morvern. Gallagher (1963), indeed, regarded the minette types (few in number though they are) as Devonian in age.

Radiometric-dating is the only certain means of dating the swarm. On the basis of the symmetry of their intensity-distribution (figs. 140 & 141), the author is obliged for the present to refer to the whole assemblage of dykes as of Permian age. The total assemblage is at least definitely pre-Triassic.

The contour-maps of the crustal-extension produced by the Permian swarm and the number of dykes per kilometre (figs. 140 & 141) are based on readings of 650 dyke-outcrops in 50 sections of total length 68km. In each of four districts the lengths of sections selected for calculation of the intensity of the swarm are measured at right-angles to the median trend. The median trend varies but little from district to district (figs. 140 & 141, equal-area rose-diagrams).

In both figs. 140 and 141 an axis of high-intensity parallels the average trend of the dykes, and this axis is offset between Lismore and the northern shores of Loch

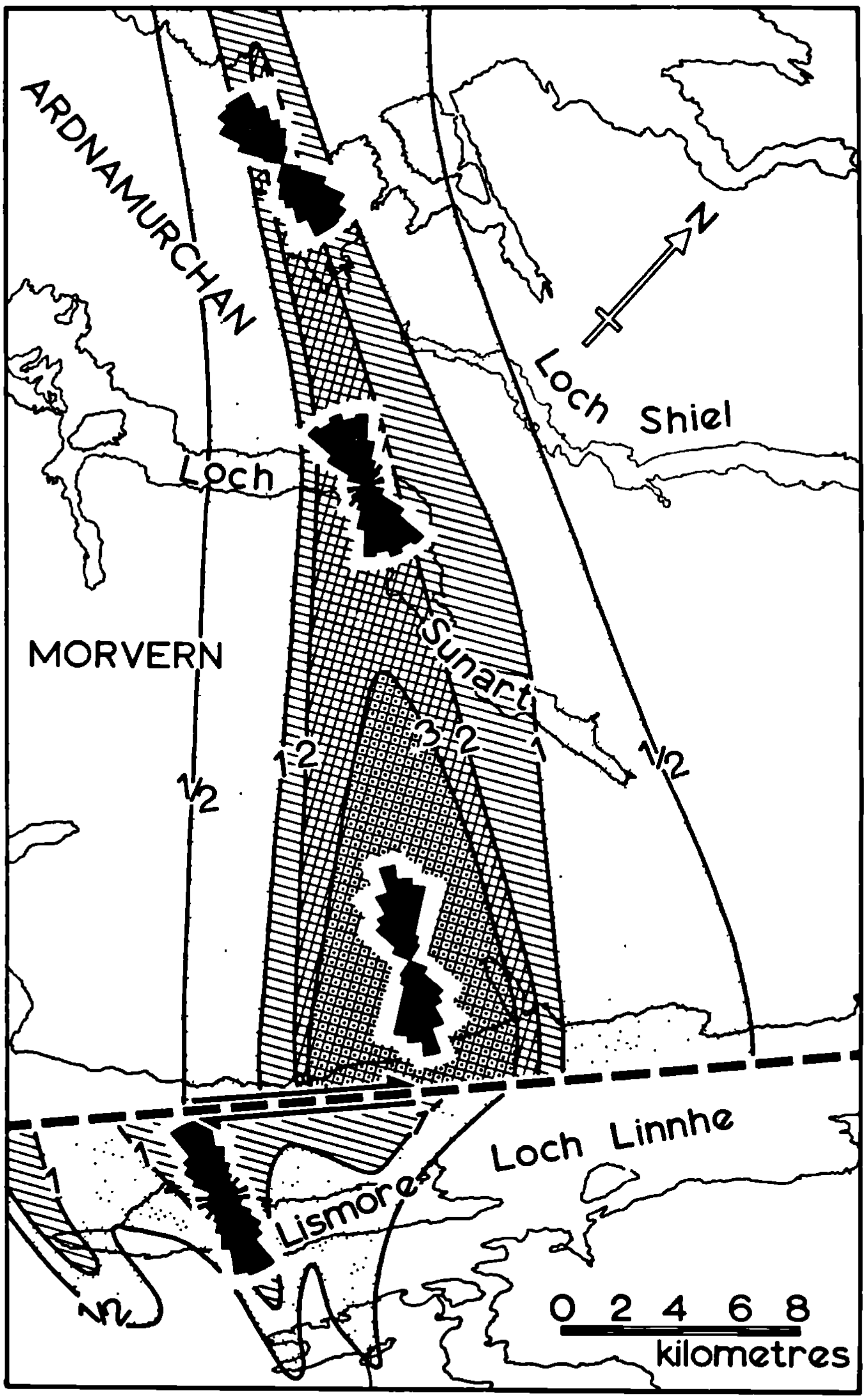

Fig.140. Percentage crustal-extension (dilation) ... Permian Dyke-Swarm of northern Argyll. (Great Glen Fault in heavy broken line.)

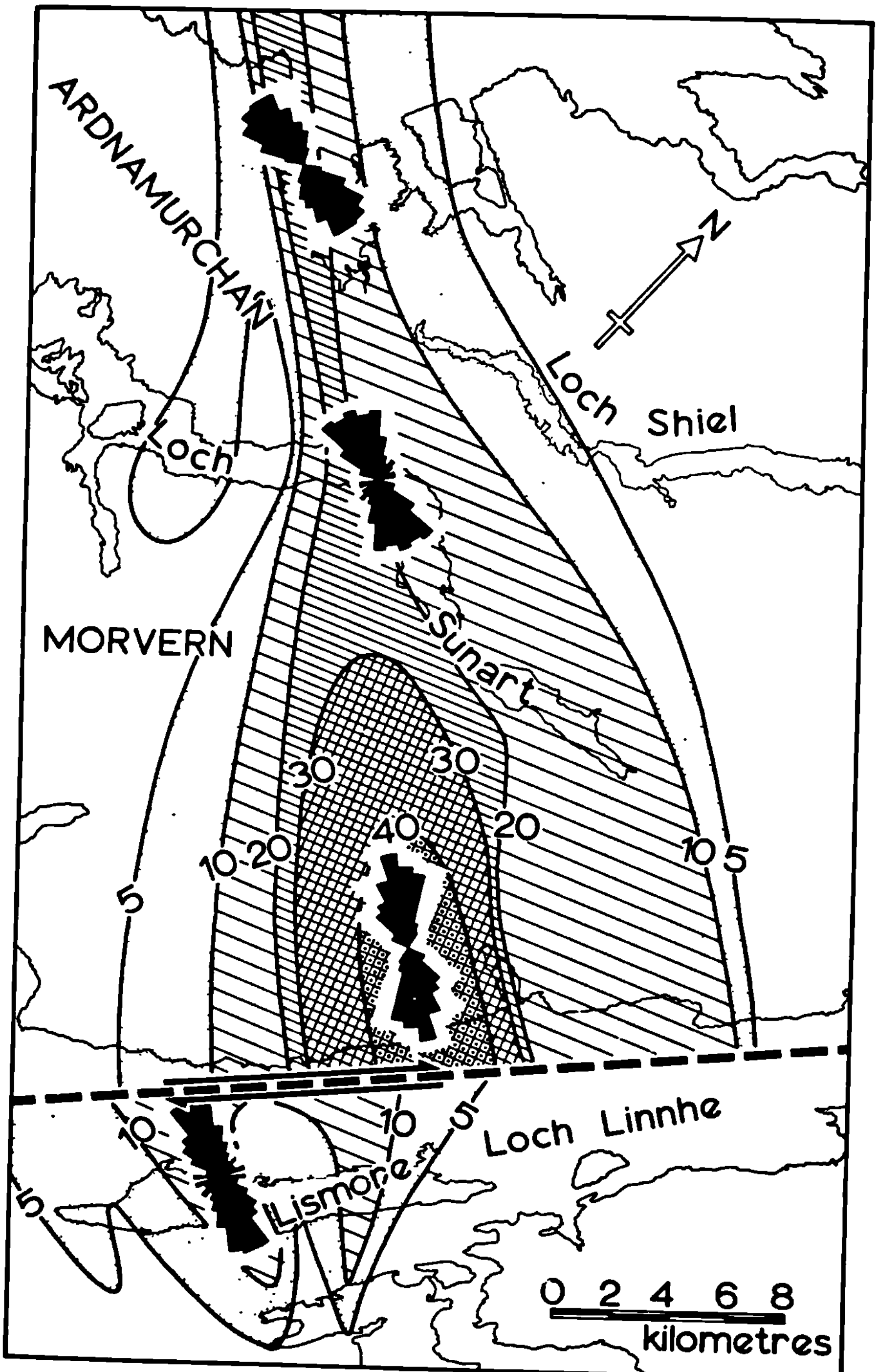

Fig. 141. Intensity of Dykes ... Number of dykes per kilometre ... Permian Dyke-Swarm of northern Argyll. (Great Glen Fault in heavy broken line.)

Linnhe. The offset of the axis is thus at the line of the Great Glen Fault (heavy broken line in figs 140 and 141). The main pre-Upper Carboniferous movement of 65 miles in a sinistral sense (Kennedy,1946,p.66) predates the intrusion of the Permian dyke-swarm. Kennedy (1946,p.67), however, stated that the "quartz-dolerite and camptonite-monchiquite dyke-swarms of Permo-Carboniferous age cross the fault-line without apparent lateral displacement".

To the south of the Great Glen Fault there is a reduction in the intensity of the Permian swarm. If as is most probable the dyke-swarm increases in intensity with depth, then a deeper level is exposed to the north of the Great Glen Fault. It is suggested that the Great Glen Fault suffered displacement with a component of downthrow to the south. However, since the dykes at the present level of erosion do not show a preferred orientation of dip northeastwards, but are in fact mostly vertical, it is likely that normal faulting alone cannot account for the offset dilation-axis. A component of dextral transcurrent displacement on the Great Glen Fault must also have occurred, amounting to as much as 7km. (figs. 140 & 141).

The Tertiary dyke-swarms of Skye and Mull are not similarly displaced at the Great Glen Fault. Hence the dextral-slip is of post-Permian date and prior to the emplacement of the Tertiary dykes. Holgate (1969) drew attention to the dislocation of an ancient river-system by dextral movements on the Great Glen Fault. This evidence and the configuration of the Tertiary and Permian dyke-swarms in the region must then indicate a late-Cretaceous or early-Tertiary age for the dextral wrench. The wrench, therefore, predates the Tertiary dyke-swarms, and does not post-date them as Holgate believed. (Evidence that the Tertiary dyke-swarm of Skye is not displaced at the Great Glen Fault is to be found in this thesis; the knowledge that the Mull dyke-swarm is not displaced at the same fault derives from the work of Sloan (1970).)

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LIST OF MAPS USED

Geol. Surv. G.B. (Scotland), 1 inch to one mile:
Sheets 80 and parts of 81,90 & 91 (Northern Skye); 31 (Applecross); 71 (Glenelg); 70 (Minginish); 60 (Small Isles); 53 (Ben Nevis); 52 (Tobermory); 51 (Coll); 45 (Oban); 44 (Mull).

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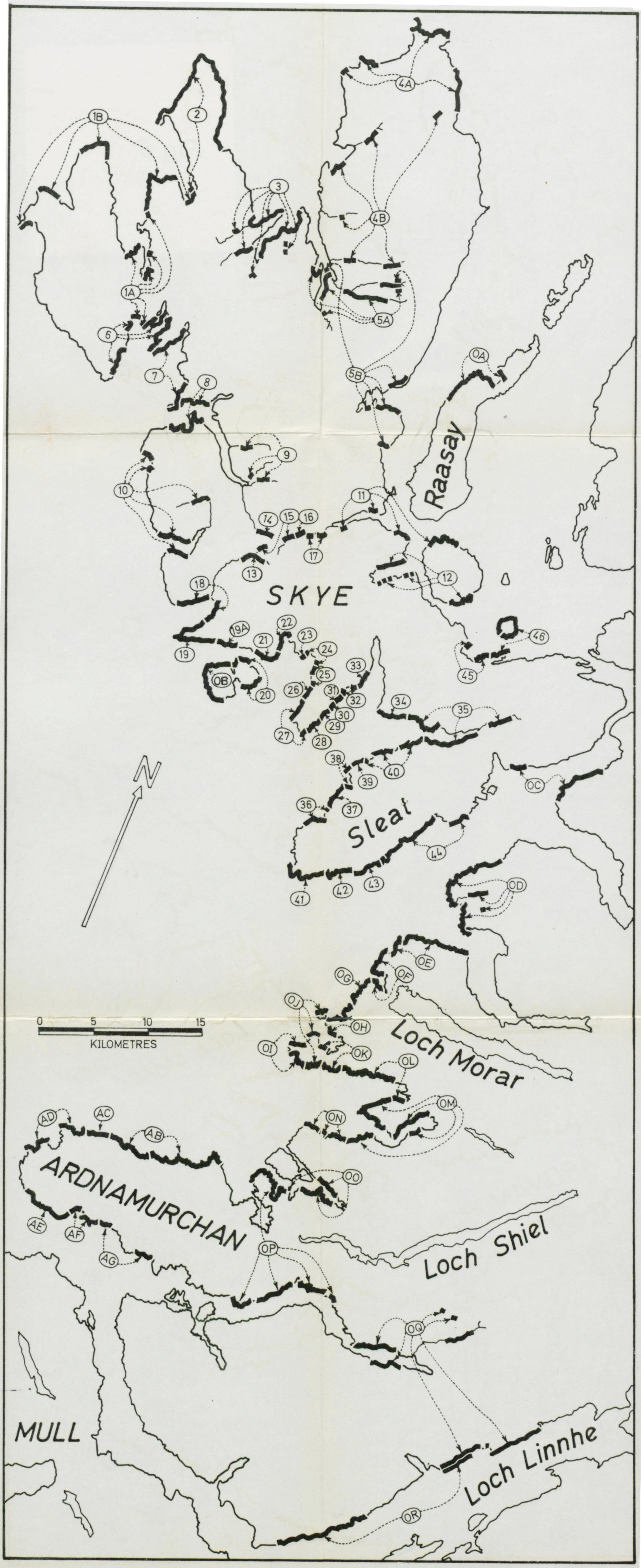


Fig. 6. LOCATIONS OF SECTIONS FOR GROUPS OF 100 and 50 DYKES

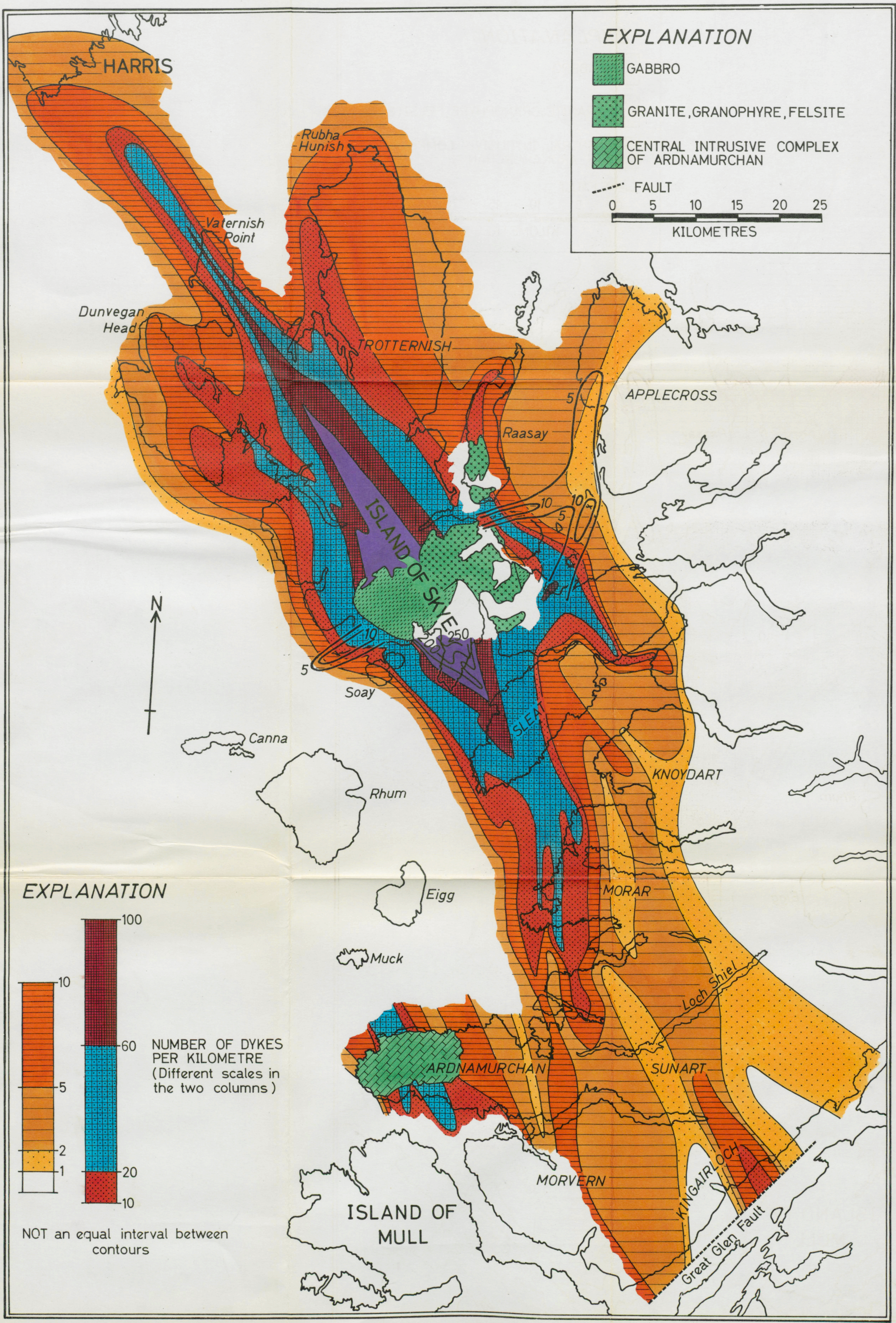
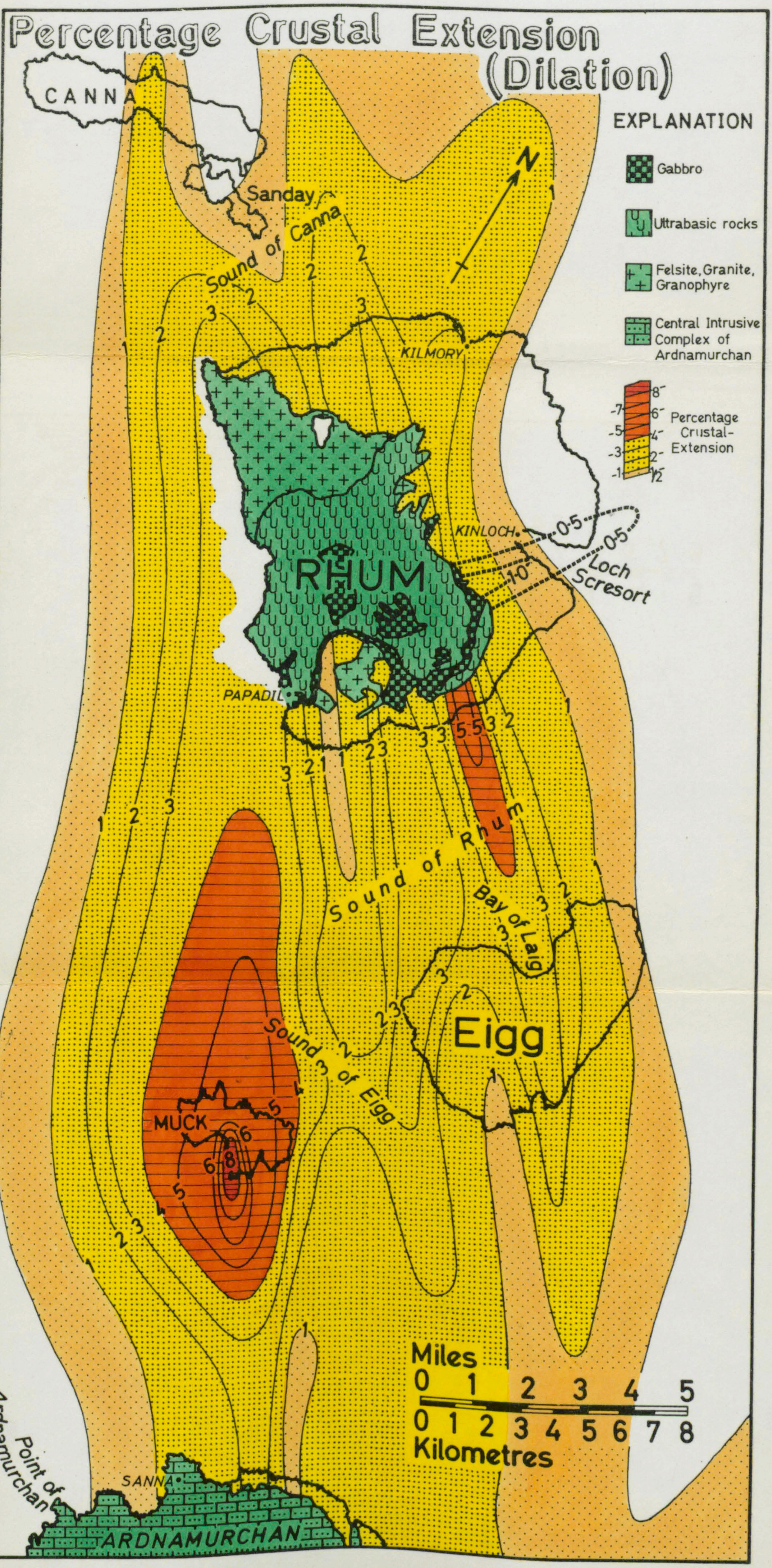


Fig. 51. *Intensity of dykes — Number of dykes per kilometre*

Loch Brittle
Loch Scavaig
STRATHAIRD
SOAY
BROADFORD
PABAY
KYLE OF LOCHALSH
Loch Alsh
Kyle Rhea
Loch Duich
GLENELG
Loch Eishort
Ornsay
Rhum
Sound of Sleat
Loch Hourn
KNOYDART
Loch Nevis
MALLAIG
MORAR
Loch Morar
Eigg
MUCK
Eilean Ighe
ARISAIG
Loch nan Uamh
Loch Ailort
Loch Eilt
Sanna Point
Ockle Point
EILEAN SHONA
MOIDART
ARDNAMURCHAN
KILCHOAN
Loch Shiel
Loch Eil
SALEN
SUNART
Loch Sunart
STRONTIAN
Loch Teacuis
MORVERN
ARDGOUR
Sound of Mull
KINGAIRLOCH
Loch Aline
ISLAND OF MULL
Great Glen Fault
Loch Linnhe
LISMORE ISLAND
BENDERLOCH
Loch Creran
Explanation
GABBRO
GRANITE, GRANOPHYRE, FELSITE
CENTRAL INTRUSIVE COMPLEX OF ARDNAMURCHAN
FAULT
Percentage Crustal-Extension of Minor Swarms
PERCENTAGE CRUSTAL-EXTENSION (DILATION)

PERCENTAGE
CRUSTAL-EXTENSION
(DILATION)
-Scale-
KILOMETRES
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
0 1 2 3 4 5 6 7 8 9
MILES
HARRIS
Renish Point
The Little Minch
Vaternish Point
Rubha Hunish
Staffin Bay
Dunvegan Head
Loch Dunvegan
DUNVEGAN
Loch Snizort
UIG
TROTTERNISH
ISLAND OF SKYE
Sound of Raasay
RONA
Loch Torridon
Loch Bracadale
Idrigill Point
PORTREE
Inner Sound
APPLECROSS FOREST
Talisker Bay
Loch Harport
Tianavaig Bay
Raasay
Loch Sligachan
Loch Eynort
CROWLIN ISLANDS
Loch Kishorn
Loch Ainort
SCALPAY
Cuillin Hills
Loch Brittle
Loch Carron
PABAY
BROADFORD
KYLE OF LOCHALSH
Loch Scavaig
STRATHAIRD
Loch Slapin
Loch Alsh
SOAY
Kylerhea
Loch Eishort
Loch Duich
GLENELG



Percentage Crustal Extension (Dilation)
EXPLANATION
Gabbro
Ultrabasic rocks
Felsite, Granite, Granophyre
Central Intrusive Complex of Ardnamurchan
Percentage Crustal-Extension
N
CANNA
Sanday
Sound of Canna
KILMORY
KINLOCH
Loch Scresort
RHUM
PAPADIL
Sound of Rhum
Bay of Laig
Eigg
Sound of Eigg
MUCK
Point of Ardnamurchan
SANNA
ARDNAMURCHAN
Miles
0 1 2 3 4 5
0 1 2 3 4 5 6 7 8
Kilometres